Geologic Hazards
'91 Workshop

February 20-21, 1991

Geologic Hazards in British Columbia

Proceedings

University of Victoria, B.C.

Conference Organizers
Ministries of:
Energy, Mines and Petroleum Resources
Transportation and Highways
Environment, Lands and Parks

B.C. Geological Survey Branch
Open File 1992-15

ERRATA - OPEN FILE 1992-15
See paper by Peter Cave.

Replace Figure 4 with this figure.

MOUNTAIN STREAM EROSION OR AVULSION				
	1:50	1:50 - 1:200	1:200 - 1:500	1:500 - 1:10 000
Minor Repair (<25%)	4	2	1	1
Major Repair (>25%)	4	4	1	1
Reconstruction	5	4	3	1
Extension	5	4	3	1
New Building	5	4	3	1
Subdivision (infill/extend)	5	5	4	1
Rezoning (for new community)	5	5	5	1

Replace Figure 5 with this figure.

DEBRIS FLOW/DEBRIS TORRENT					
	1:50	1:50 - 1:200	1:200 - 1:500	1:500 - 1:10 000	<1:10 000
Minor Repair (<25%)	5	2	2	1	1
Major Repair (>25%)	5	4	2	1	1
Reconstruction	5	5	4	3	1
Extension	5	5	4	2	1
New Building	5	5	4	3	1
Subdivision (infill/extend)	5	5	5	4	1
Rezoning (for new community)	5	5	5	5	1

Replace Figure 6 with this figure.

SMALL-SCALE LOCALIZED LANDSLIP					
	1:50	1:50 - 1:200	1:200 - 1:500	1:500 - 1:10 000	<1:10 000
Minor Repair (<25%)	5	2	2	1	1
Major Repair (>25%)	5	4	4	1	1
Reconstruction	5	4	4	3	1
Extension	5	4	4	3	1
New Building	5	4	4	3	1
Subdivision (infill/extend)	5	5	5	4	1
Rezoning (for new community)	5	5	5	5	1

Replace Figure 9 with this figure.

MAJOR CATASTROPHIC LANDSLIDE					
	1:200	1:200-1:500	1:500-1:1 000	1:10 000-1:10 000	<1:10 000
Minor Repair (<25%)	5	2	1	1	1
Major Repair (>25%)	5	5	2	1	1
Reconstruction	5	5	5	1	1
Extension	5	5	5	1	1
New Building	5	5	5	1	1
Subdivision (infill/extend)	5	5	5	5	1
Rezoning (for new community)	5	5	5	5	5

GEOLOGIC HAZARDS IN BRITISH COLUMBIA

Proceedings of the
Geologic Hazards '91 Workshop
February 20-21, 1992, Victoria, B.C.

Compiled and edited by:
Peter Bobrowsky

British Columbia
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PREFACE

The impetus for the Geologic Hazards '91 Workshop and this subseqent proceedings volume derive from a combination of factors including new government initiatives, a trend toward increased public awareness of geoscience concepts, as well as the proclamation of the 1990's as the International Decade for Natural Disaster Reduction (IDNDR). This latter proclamation, by the United Nations Assembly, illustrates the global responsibility to decrease the estimated annual death toll of 250,000 people and $50 billion in damage costs which plague humankind due to natural disasters.

In 1989, after a 21 year hiatus, a Surficial Geology Unit (SGU) was reinstated under the aegis of the British Columbia Geological Survey Branch. Interviews by the SGU staff with numerous specialists subsequently helped identify problems and needs in B.C. surficial geology. Geological hazards were targeted as one of the elements in surficial geology which warranted prompt attention. However, before embarking on an active program in hazards research, the SGU staff sought to assess the state of the geological hazards database for British Columbia. It became readily apparent that the lack of a centralized information repository and the absence of a coordinating body for geological hazards research precluded a simple database assessment.

In response to the above shortcomings, scientists within the ministries of Energy, Mines and Petroleum Resources, Transportation and Highways as well as Environment, Lands and Parks organized a two-day workshop in Victoria. The intent of the workshop was to identify key players, programs and problems in British Columbia geological hazards studies. To this end, the gathering was successful, as approximately 150 individuals, including representatives from provincial/federal/state/ municipal governments, academia, and private industry, gathered at the University of Victoria campus on February 20 and 21, 1991 to listen, learn and lecture on a variety of themes related to British Columbia geological hazards. Key note lectures were interspersed with interactive sessions consisting of small groups of individuals; the two approaches intended to promote and maximize upon audience participation. Both aspects are presented in this proceedings volume which contains papers and/or extended abstracts of the key note speakers as well as a summary review paper by the Workshop Steering Committee. The Steering Committee on Geologic Hazards was assembled immediately after the meeting to synthesize the multitude of comments and suggestions offered during the course of the workshop. Their paper provides written direction as to the future course of hazards work within the province based on the combined sentiments of all workshop participants. In an effort to generate an unbiased review, the committee consisted of representatives from the federal, provincial and local government, academia and private industry.

British Columbia is under constant threat from numerous and potentially devastating geological hazards. This volume addresses the most significant natural hazards affecting the people of the province. Leading experts in a variety of disciplines present up-to-date, cogent and informative reviews on such phenomena as earthquakes, volcanic eruptions, tsunamis, landslides, shoreline erosion and flooding. Related state-of-the-art papers discuss the importance of risk assessment, hazard threshold acceptability, hazards in the future, consultants' roles, hazards legislation as well as federal and provincial emergency response programs. This publication will prove a useful library addition to all individuals active or interested in geological hazards research, mitigation and policy management.

Geologic Hazards '91
Organizing Committee
Peter T. Bobrowsky (EMPR)
Robert Buchanan (MoTH)
Victor M. Levson (EMPR)
Donald R. Lister (MoTH)
Bruce Thomson (MOF)
March 1992

RECOMMENDATIONS OF THE GEOLOGIC HAZARDS WORKSHOP - BY THE STEERING COMMITTEE ON GEOLOGIC HAZARDS

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INTRODUCTION

Geologic hazards are natural earth processes such as landslides, floods, earthquakes and volcanic eruptions which can threaten the lives, property and well being of people. Snow avalanches, landslides and floods have claimed scores of lives and have accounted for many millions of dollars of property damage and lost economic activity in British Columbia. Such hazards are increasing concerns because, with urban growth and the boom in recreational communities, development is frequently intruding into areas where hazardous events may occur relatively frequently. Furthermore, the results of recent geologic and geophysical research suggest that Vancouver Island and the Lower Mainland may be prone to great earthquakes. A major earthquake, in such a populated area, could claim hundreds of lives and cause billions of dollars in damage.

On February 20 and 21, 1991, more than 130 experts on various aspects of geologic hazards and public safety from British Columbia, Yukon, Alberta and Washington State assembled at the University of Victoria for a workshop on geologic hazards. Only one other such gathering, in 1976, had previously taken place. Those attending the meeting represented hundreds of person years of experience, and most of the intellectual resources available to the people and Government of British Columbia, in the study, mitigation, and control of geologic hazards (see List of Participants). Organization of the meeting was a joint effort of the British Columbia ministries of Energy, Mines and Petroleum Resources, Transportation and Highways, and Environment, Lands and Parks.

The goals set by the organizers of the workshop were to identify:

1) current geologic hazard programs in the province;

2) existing geologic hazard legislation;

3) existing agencies responsible for the coordination and implementation of geologic hazards research and their programs for mitigation and avoidance;

4) future geologic hazard research, monitoring needs and priorities; and,

5) means of establishing a geologic hazards information and research data base.

The format of the workshop for both days included a morning of topical papers followed by an afternoon of small group workshop sessions concluded by a discussion by all participants. Day one was concerned with individual types of hazard phenomena. Day two addressed the management and mitigation of hazards with an emphasis on developing action plans identifying authorities responsible for these activities.

At the conclusion of the workshop, a steering committee was struck to report the findings and recommendations of the workshop.

The Committee has divided the recommendations into three headings which followed naturally from workshop discussions:

1) immediate steps for the protection of people from geologic hazards;

2) establishment and incorporation of a provincial geologic hazards data base into urban and regional planning; and,

3) scientific recommendations which address specific or related geologic hazards.

IMMEDIATE STEPS FOR THE PROTECTION OF PEOPLE FROM GEOLOGIC HAZARDS

Avoidance of areas susceptible to geologic hazards is the cheapest and most effective method of protection. It is usually far cheaper to manage land use than it is to respond to a major disaster. Avoidance of geologic hazards can be done by the people themselves, through application of their own knowledge, or imposed by government. The first is preferable but at least elements of the latter are often inevitable.

The Conference makes the following recommendations:

1) A program to educate the public about geologic hazards, including earthquakes and landslides, should be implemented through an agency such as Provincial Emergency Program in consultation with the Association of Professional Engineers and Geoscientists. Video presentation would be a particularly effective medium. These presentations should particularly target the school-age population as awareness of natural hazards should be an essential component of safety education. They should also be presented on the Knowledge Network or other television stations especially during events such as Emergency Preparedness Week.

2) Flood plains are among the most easily identified areas subject to geologic hazard. All areas at risk from a flood of a standard probability, for example greater than 1/200, should be identified and development in these areas should be limited to certain compatible uses. Where streams are ungauged, the "effective" flood plain boundary could be substituted for the 200 year flood limit. Alluvial fans require a modified zoning policy to account for the different behavior of water and debris flows.

3) With evidence mounting to suggest that southwestern British Columbia could experience a great earthquake, public and commercial buildings such as schools which predate earthquake resistant construction practices should be brought up to contemporary standards expeditiously or be demolished.

4) Provincial guidelines are needed for development, particularly building, on potentially hazardous land. These guidelines should show developers how to approach the question, what is required to be examined and legislation that has to be met. A short preamble discussing the nature and seriousness of geologic hazards should be included. The need for carrying out such studies at the very start of a development proposal should be emphasized to ensure that the developer is not wasting his money on a seriously hazardous site.

INCORPORATION OF THE GEOLOGIC HAZARDS DATA BASE INTO URBAN AND REGIONAL PLANNING

Incorporation of a geologic hazards data base into urban and regional planning is a sensible concept few would argue with. Such integration already takes place on large projects such as highway routing and it is routinely done by many municipal governments. To effectively incorporate geological hazard information into the planning process on a provincial scale and to obtain uniform results, two factors must be in place; a provincial data base, and agreement on what constitutes acceptable or unacceptable risk.

Each level of government from federal and provincial geological surveys and environment ministries to municipal engineering departments have accumulated files, reports or formal data bases which contain geologic hazard-related information.

To integrate these many past and future studies and data bases into a complete provincial data base involves significant challenges. Legislation requiring disclosure of information, continuity of government policy and funding is required in order to set up and maintain such a data base on a permanent basis. However, without this quality and consistency of effort, everyone from an individual interested in evaluating the safety of a single building site to a major developer must wade through the files and reports of many agencies. Furthermore, work by private consultants, unless on file with public agencies, is completely inaccessible. This may result in the needless costly repetition of work or oversight of a previously identified hazard.

Assuming that all available geologic hazard information is in hand, what constitutes acceptable and unacceptable risk and who should decide? Evaluation of geologic hazards requires a high degree of judgment and involves many questions. For example. What is the nature of the hazard? What is at risk? For how long would the activity or structure at risk exist? Would the hazardous event occur with or without warning? Will the liability be societal or individual? Can the hazard be assigned a statistical probability? If the hazard is accepted, as for example, the inevitability of a large earthquake, can anything be done to mitigate the damage, such as banning residential construction from areas likely to amplify shaking or upgrading building codes?

The Conference makes the following recommendations:

1) A central registry of all geotechnical and other geologic hazard-related reports should be established and operated by the British Columbia Geological Survey Branch (BCGS). This data base would be similar to those currently collecting water, oil and gas drilling information. Private reports could be held confidential for a given period before coming into the public domain. As a bare minimum, the subject matter and the geographic area of the report would be listed in a geographical information system (GIS) which would be available to the general public. This recommendation needs to be a legal requirement for new development and investigations. Compliance with the registry should be enforced.

2) A program should be instituted to incorporate existing reports and data into this central registry.

3) The detailed workings of such a provincial geologic hazards data base should involve further input from the geologic hazards community. During the Geologic Hazards Workshop, suggestions ranged widely as to how this data base should be funded and whether it should be part of a larger institute for geologic hazards research. A follow-up workshop dealing with this theme should be held in 1993.

4) Governments should consider establishing acceptable risk thresholds for hazards other than floods. Where possible, avoidance and mitigation measures for these other hazards should be standardized in the building codes as they are for wind, snow load and earthquake resistance.

SCIENTIFIC RECOMMENDATIONS

The dangers posed by geologic hazards to lives and property cannot be adequately evaluated unless they are first recognized and understood. Those present at the conference held the view that substantial net savings will accrue to British Columbians through geologic hazard research. The following recommendations identify geologic hazards research initiatives that are needed to adequately assess the risks these hazards present to society and to provide the information necessary for urban, regional and emergency planning. Attendant recommendations are also made concerning more effective administration of hazard research funds. The recommendations resulting from the conference are organized topically:

EARTHQUAKE RESEARCH

1) Detailed definition of areas expected to experience similar ground motions during earthquakes is required in urban centres along coastal British Columbia. Such *microzonation* is an essential tool for urban and emergency planning in earthquake-prone areas. British Columbia is lagging substantially behind the San Francisco Bay area in implementing this vital work. This work will require a cooperative effort among provincial and federal geological surveys and

the Canadian Committee for Earthquake Engineering (CANCEE) with special advice from university researchers and private sector experts.

2) Current efforts to predict the seismic responses such as amplification and resonance of shaking and liquefaction within the same *microzones* should be continued and enlarged.

3) The products of recommendations [1] and [2] should be rapidly incorporated into upgraded building codes, safety evaluation of existing buildings, and land use planning. It should also be used to predict and evaluate "second day" earthquake hazards such as, flooding caused by earthquake induced-damage to dykes along the Fraser River.

4) Paleoseismicity studies, *i.e.* studies of the evidence of past earthquakes which can be deduced from geologic deposits and features, should be continued and broadened by the Geological Survey of Canada (GSC) and university researchers. Because of the short duration of written history in British Columbia, this is one of the few ways that the frequency and magnitude of the earthquake hazard can be evaluated.

LANDSLIDE RESEARCH

1) A complete geographical view of hazards presented by high magnitude infrequent landsliding (*e.g.* the Hope Slide), and low magnitude frequent landsliding (*e.g.* debris torrents along Howe Sound), can only be obtained through systematic terrain mapping. Terrain mapping is currently being done exclusively by the Geological Survey of Canada. An expanded program of systematic terrain mapping at a scale of 1:100 000 should be undertaken cooperatively by the Geological Survey of Canada and the British Columbia Geological Survey Branch.

2) Urban areas and transportation corridors should be targeted for detailed landslide mapping, along with terrains particularly prone to landsliding such as incised glacial lake deposits and volcanic massifs. This mapping should identify not only past and potential landslides but also the limits of runout areas. Landslide mapping in these areas should be carried out by local planning agencies or operated as cooperative efforts among local planning agencies and geological surveys.

3) A central digital data base should be established by the British Columbia Geological Survey Branch in order to study and predict the occurrence, volume and runouts of debris flows and debris torrents as these hazards may not be readily identifiable from mapping alone. Analysis of past events is required to predict which basins are likely to produce debris torrents and debris flows in the future.

FLOOD RESEARCH

1) A study of the role of land uses, such as logging and urbanization, on frequency and magnitude of floods and flood transported sediment should be instituted. Since jurisdiction over this issue is not well defined for extant agencies, a cooperative study among provincial Forestry and Environment, Lands and Parks ministries is suggested.

2) The hydrology of steep water courses, fans and extreme flood events need to be better understood. Expertise in this area is widely distributed among federal and provincial Environment ministries, university researchers and private consultants. The British Columbia Ministries of Highways and Transportation, and Environment, Lands and Parks are logical lead agencies in these investigations.

3) The Provincial Floodplain Mapping Program needs to be better funded, and accelerated.

MARINE AND SHORELINE HAZARDS

1) The current state of knowledge of erosion hazard along the British Columbia coast should be reviewed and supplementary erosion hazard mapping and inventory should be carried out where required.

2) Populated and developed coastal areas should be investigated and inventoried for their susceptibility to earthquake-induced tsunamis and liquefaction. The GSC is the logical lead agency for this initiative with assistance from university researchers.

3) Investigations should be made as to the susceptibility of populated deltas to delta-front submarine landsliding. This is particularly crucial for the Fraser Delta where critical power and telephone lines run offshore.

VOLCANIC HAZARDS

1) A catalogue and data file of known volcanic centres should be compiled and potential hazards to nearby communities or public works evaluated by the GSC and advisory agencies. This would include impact on lives and property and also impact on such things as fish and wildlife habitat.

2) Priority should be given to eruption impact studies of the two recently active volcanic centres closest to urban areas, Mount Baker and Mount Meager. The former case will require a combined US-Canada-Washington State-B.C. effort.

3) The GSC seismograph network should be expanded and upgraded in northern British Columbia and Yukon in order to monitor volcanic centres in those areas.

SCIENTIFIC RESEARCH POLICY

1) Geologic hazard research should be reviewed, priorized and awarded by engineers and geoscientists familiar with geologic hazards. Presently, funding for such research is generally on a reactive and *ad hoc* basis.

2) Expertise in the field of geologic hazard investigation is spread among provincial and federal agencies as well as the private sector. Funding and delivery for this research should be shared between both levels of government, perhaps along the model of Mineral Development Agreements.

3) Closer coordination should be fostered between the various levels of government involved in geologic hazard research in order to maximize the benefits and minimize duplication of effort. A steering committee on geologic hazards, made up of representatives from federal, provincial and local governments could oversee coordination.

HAZARDS IN THE FUTURE: A GLOBAL PERSPECTIVE

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ABSTRACT

Prediction of natural hazards in the future (e.g. global change, earthquake and volcanic activity) will remain a precarious exercise. Modern society has yet to experience certain severe natural hazards known to have occurred earlier in human history. However, increasing hazards to humankind are in part a consequence of human activities and future projections of their consequences may have some validity. Humankind now transports more earth materials annually than does Mother Nature. The human population is anticipated to double by about 2030 AD, resulting in severe problems of sustainable development, resource depletion, environmental degradation, and stability of social and political systems. Critical decisions remain on the extent to which we manage the planet and its natural systems as opposed to living in harmony with existing systems. Technological advances will occur, but will societies have the economic resources to deploy them? The threat and consequences of global climate changes are of immediate concern. However, modern societies have concentrated their populations in fixed urban centres, which are inflexible structures to cope with shifts in climatic belts or sea level change. Humankind has yet to achieve an effective international organization (cf. United Nations Organization) to develop rapid consensus on international hazard crises. The embryonic program of the International Decade of Natural Hazard Reduction (IDNHR) offers an opportunity to develop such an international capability during the 1990's. The proposed Canadian program of the UN/IDNHR should be strongly supported and there are special opportunities for leadership by specialists or agencies in British Columbia.

PAST AND FUTURE NATURAL HAZARDS

Both the geologic and archaeological record clearly demonstrate that the world can be a particularly hazardous place for life to exist. There appears to have been times of quiescence or stasis interposed by periods of significant to catastrophic change. In some of the major extinction events (*e.g.* end of the Ordovician, Permian, and Cretaceous periods) as much as 25-50 per cent of the total species in the world biota may have become extinct. At the present point in human history, our species appears to view the forces and cycles of nature as being rather passive and unlikely to exhibit much variation in the foreseeable future. With continued technological advances, humankind has developed an attitude that it has power over nature, and that most of nature can be harnessed and managed for its own benefit.

With the series of agricultural, industrial, green, and information technology revolutions has come a phenomenal growth in world population, largely accommodated spatially through urbanization. Within the time it takes a tree seedling to grown to maturity in the Pacific Northwest, the world's population will have quadrupled at present growth rates. If we accept optimistic demographic estimates, perhaps the growth of world population will begin to level off at 11 billion by about 2030 AD. Although there are serious matters of education, housing, health, and the feeding of this increased population, a major issue perhaps not fully comprehended is the extent of the various forcing factors created by this number of people. Issues of waste disposal and pollution, resource depletion, global warming, effect on the ozone layer, physical modification of the earth's surface, and reduction in biodiversity are profound problems for which there is limited time for research, education, correction and ultimately a necessary drastic reduction in the causes [the size of the world's population and the rate of consumption of resources].

This increase in population has resulted in an intense niche-partitioning of available space. The trend to urbanization, results in the massive investment in fixed assets (sprawling conurbations) that provide little flexibility against changes in natural systems (*e.g.* global warming, sea-level rise). Along with the niche-partitioning has come an ever pressing drive to improve efficiency of systems (*e.g.* economy, automation and robotics, energy). This evolution itself is perhaps a natural development, comparable to the well known sequence in many ecosystems (*e.g.* growth of coral reefs) which progress from a pioneer stage through a domination phase to climatic stage. The latter phase is commonly a prelude to an ecologic disaster when the system has become too complex and specialized that it reduces its capacity to respond to major environmental changes. Humankind, in other words, is forcing many of the natural systems to their limits. Some create natural negative responses (global warming, sea-level rise, ozone depletion, erosion of top soil, resource depletion, groundwater contamination, etc.). Others simply reduce the ability of the economic and social fabric of society to respond to natural catastrophes (*e.g.* major volcanic eruptions, earthquakes, crop failures). As the world population grows, becomes more densely localized, and increases its debt load, it becomes more vulnerable to such extreme natural hazards. The national and international programs for aid, hazard reduction and food reserves may be woefully inadequate for such future catastrophes. Engineers in developed countries may have accepted, through national building codes, the concept of the extreme hundred-year event (storm, flood) in designing structures (bridges, sea-walls, etc.) but aid agencies and nations have not yet conceived of support systems to cope with certain extreme natural hazards largely unexperienced in recent human history.

A few examples of future natural hazards include climate warming, sea-level rise, earthquakes, and volcanic activity. The extent of potential global warming is becoming more evident following global analyses with estimates of a +3°C change over the next century in mean world temperature (*e.g.* Intergovernmental Panel on Climate Change, 1990; Mungall and McLaren 1990) - a rate greater than in any equivalent period over the last 10,000 years. The effects of such temperature changes will be most profound in polar areas and will have a major impact on permafrost; the release of gas hydrates will contribute further volumes of methane to the atmosphere, accentuating the greenhouse effect. The IPCC report (1990) clearly outlines the potential consequences of continued use of fossil fuels at present emission levels. Although there are significant efforts to reduce consumption, reduce emissions, increase combustion efficiency as well as efforts to develop new energy systems (*e.g.* hydrogen fuel cell), the current rates of consumption are alarming, and in the People's Republic of China alone, there are over 60 new coal-fired generating stations being constructed or designed. Given that CO_2 has a residency time of about a century in the atmosphere, it is simply not possible to force this system and expect to be able to pull back from the brink at the last moment. Again, nations invest vast amounts in their energy systems, and many are dependent on one dominant fuel source; flexibility is limited, and scheduled time frames for responding to change may be impossible to implement.

If global warming was to occur at the rates estimated above, then a sea-level rise of 65 cm may occur over the next century (*e.g.* IPCC, 1990; Mungall and McLaren, 1990), again with significant regional variations (*e.g.* Alley, 1991). Increased sea-level and enhanced storm tracks can create havoc in highly populated low lying areas as was seen in 1991 in the coastal zone of Bangladesh or the extensive flooding experienced by sinking urban centres such as Venice, Italy and Bangkok, Thailand. In recent decades many nations (*e.g.* USA) have experienced a population migration to coastal cities, thereby increasing the potential impact of the hazard of sea-level rise. The combined impact of oceanic changes and resulting local climate change, has been documented by Wells (1990). Wells found that a series of changes to Andean civilizations along the coast of Peru could be correlated to mega-El Nino effects which produced enhanced rainfall in the Andes, flash floods, and the destruction of both arable farmland and the particular culture developed at those times.

It has been almost a century since a very explosive volcanic eruption has occurred. The 1991 eruption of Mount Pinatubo in the northern Philippines has wrought considerable destruction to the local region, including the U.S. military base. In the Pacific Northwest, the eruption of Mount St. Helens in May 18, 1980 revealed the significant forces of a relatively modest eruption [many facets well documented by the papers in *Geoscience Canada*, 1990, Volume 17]. If one or more major explosions took place, similar to, or larger than, that of Tambora in 1815, which apparently lowered global temperatures for at least a year due to ash concentrations in the upper atmosphere, would the reduction in world crop production drastically exceed the amount of food supplies in storage?

The potential major natural hazards for the future noted above are those that have existed in the past. Only now their effects may be more enhanced or, with increased and localized population, their effects may be more disastrous. The total threat to the planetary systems has been aptly captured recently in the book published by the Royal Society of Canada: Planet Under Stress (Mungall and McLaren, 1990). This is an admirable source for general reading and for more specific references.

TOWARDS A SOLUTION

It is evident that three aspects are required in moving towards a solution of reducing the effects of major hazards in the future: a) more research on natural systems; b) reduction of anthropogenic forcing; and, c) an improved international program for hazard reduction.

Public awareness of environmental problems, particularly climate change, has increased dramatically over the last decade. It has resulted in an improved level of government support for environmental research, although this is still far short of required levels. International programs such as the International Geosphere-Biosphere Program (IGBP or Global Change) are marshalling much scientific talent to address many separate programs. In Canada, the Royal Society of Canada is the lead agency coordinating the Global Change Program.

The reduction of levels of anthropogenic forcing is an even larger issue with greater uncertainty for success. An international meeting scheduled for Brazil in 1992 will attempt to define certain acceptable protocols for environmental quality. It builds on the Brundtland Commission Report (World Commission on Environment and Development, 1987) which helped advance the concept of sustainable economic development.

This United Nations initiative was undertaken during a period when others were advocating that the 1990's should be the International Decade for National Hazard Reduction (Advisory Committee on IDNHR Report, 1987). This report provides another fine source that reviews natural hazards and offers a plan to reduce their effects. To be successful, the IDNHR must be a network of national programs and in Canada the initiative was seized jointly by the Royal Society of Canada and the Canadian Academy of Engineering. Their recent report (July 1990, reprinted March 1991) considers the problem of national hazards and reviews the responsibilities and management structures presently in place in Canada. It recommends that the Government of Canada formally proclaim Canada's participation in the Decade and develop a program of action. It offers some specific recommendations for a National Committee and identifies the principal groups likely to be represented on the committee.

Within Canada, British Columbia is perhaps the province most prone to natural hazards (*e.g.* earthquakes, volcanic activity, landslides). The province is therefore in a position to take the lead in developing programs and participating actively in the Canadian program. There are many government and university laboratories and a strong industrial base all with expertise in various aspects of research and monitoring of natural hazards. Many papers in this volume deal with specific issues and hazards. The overall solution requires a comprehensive strategy within a well organized and funded national program which, in turn, is part of the international program of the United Nations. Such a program may be viewed as a sound insurance plan. Many countries can simply not afford the costs incurred by natural disasters and the debt-ridden economies of the developed nations offer limited resources to provide substantial relief aid. A fundamental challenge in this particular program, being so complex in the range of hazards and being on a global scale, is to develop adequate data bases and to exchange information in an effective way (Gravesteijn and Rassam, 1990; Ausubel, 1991) Some most recent articles on the IDNHR and in particular hazards and possible solutions are contained in the March 1991 issue of *Episodes* (International Union of Geological Sciences, Volume 14).

In summary, natural hazards will in future have a greater impact on humankind given the larger more localized population structure and the increased anthropogenic forcing effects. Severe hazards may test the ability of some nations to maintain social and economic order. Of particular concern is the scale of anthropogenic forcing of natural systems which is both enhancing natural hazards and creating new ones. The recognition of the threats posed by such hazards has led to the proposal for the 1990s to be an International Decade of Natural Hazard Reduction. This program is in its formative stage, yet offers the best solution to develop and manage a global strategy. A proposal for a Canadian program as a component has been advanced and should be supported. Within this Canadian effort, British Columbia must play a special role, being particularly prone to natural hazards and to having considerable expertise to help secure solutions.

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SEISMIC HAZARD IN THE LOWER MAINLAND

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ABSTRACT

Earthquake damage depends on: the intensity of shaking; the type of building or structure; and the nature of the foundation soil. Dr. Garry Rogers addresses seismic aspects and possible intensities of shaking. This presentation concentrates on the foundation soils and their effects on earthquake damage in the Lower Mainland.

Deep deposits of loose and soft soils such as underlie the Fraser Delta can: amplify the shaking; cause a shift in the predominant period that will affect tall buildings; and induce liquefaction. For these reasons the Delta is likely to suffer much more damage than other areas in the event of a major earthquake. These aspects will be discussed and lessons learned from other seismic areas will be investigated.

Examples of severe amplification effects in Mexico City, 1985, and San Francisco, 1989, will be examined together with examples of liquefaction damage in Niigata, 1964, and San Francisco, 1989. This experience will be used to estimate the likely damage in the Lower Mainland.

Extensive zones of liquefaction are predicted to occur in the Fraser Delta in the event of a major earthquake and are likely to result in severe damage. Damage to buried services such as water, gas, sewer, electricity and telephone would be very severe due to the large differential movements of the surface crust. Damage to bridge and overpass structures, and the George Massey Tunnel could also be severe. The dyking system will likely suffer severe cracking, and flooding is a possibility. Light wood structures supported on the crust are likely to suffer light to moderate damage. However, older taller buildings supported on piles could suffer very severe damage due to loss of pile support.

A tsunami generated by a liquefaction induced slump at the face of the Delta is a possibility and will be discussed.

INTRODUCTION

Earthquake damage depends on: the intensity of shaking; the type of building or structure; and the nature of the foundation soil. Dr. Gary Rogers addressed seismic aspects and possible intensities of shaking. This presentation concentrates on the foundation soils and their effects on earthquake damage in the Lower Mainland.

Deep deposits of loose and soft soils such as underlie the Fraser Delta can: amplify the shaking; cause a shift in the predominant period that will affect tall buildings; and induce liquefaction. For these reasons the Delta is likely to suffer much more damage than other areas in the event of a major earthquake. These aspects will be discussed and lessons learned from other seismic areas will be investigated.

Experience at Mexico City during the 1985 earthquake showed that a major cause of damage was the very high amplifications of acceleration that occurred as the motion propagated upwards through the soft clay lake bed deposits. A similar amplification occurred in the San Francisco Bay muds and caused much of the damage in San Francisco and Oakland during the 1989 Loma Prieta earthquake. In addition, liquefaction of loose sand fill placed on top of the Bay mud greatly added to the damage where it was present, as for example in the Marina district.

In much of the Fraser Delta, natural deposits of loose to medium dense sands overlie deep silt and clayey deposits, so that the combined effects of both amplification and liquefaction are a possibility in the event of a major earthquake, *i.e.*, the amplified motions are more likely to trigger liquefaction.

Geological evidence has recently come to light indicating that liquefaction has occurred in the Delta in the recent past. Excavation for the foundations of Kwantlin College in Richmond have revealed cracks in the surface crust that are filled with loose sand. Such features are consistent with the loose sand underlying the crust having liquefied and flowed upward into cracks formed by differential movements. Similar features were observed in the crust from the Saguenay earthquake in Quebec, 1988. Geologists from the Geological Survey of Canada are dating the Richmond deposits, so that it should be possible to determine when this liquefaction occurred. The purpose of the excavation was to allow densification of the sands beneath the College to prevent just such liquefaction from occurring in a future major earthquake.

Extensive zones of liquefaction are predicted to occur in the Fraser Delta in the event of a local major earthquake and are likely to result in severe damage. Experience at Niigata, Japan, 1964, and San Francisco, 1989 indicate that damage to buried services such as water, gas, sewer, electricity and telephone would be very severe due to the large differential movements of the surface crust. Damage to bridge and overpass structures, and the George Massey Tunnel could also be severe. The dyking system would likely suffer severe cracking, and flooding is a possibility. Light wood structures supported on the crust are likely to suffer light to moderate damage. However, many of the older taller buildings supported on piles could suffer very severe damage due to loss of pile support.

Could a tsunamis or earthquake-generated tidal wave occur? Tsunamis are generally associated with tectonic movement of the ocean floor, such as occurred off the coast of Alaska in 1964, causing great damage there, as well as in Port Alberni, and as far south as Oregon. However, much of the damage in Alaska was caused by local tsunamis generated by underwater slumping of loose deltaic soil deposits. These deposits were triggered to liquefy and flow by earthquake shaking. Because the tectonic movements of concern here would occur west of Vancouver Island, local slump-generated tsunamis would likely cause more damage in the Lower Mainland than an earthquake-generated tsunami.

There is evidence of the remains of very large slump debris in the Strait of Georgia resulting from a slide at the Delta face. Slumps of this size could be triggered by an earthquake and would cause very large tsunami waves. The waves would be generated at the face of the Delta which is 4 or 5 kilometres west of the dyked area. However, the resulting 2 or 3 waves at the dyke could be a high as 6 metres and would be very damaging to structures located near the dykes, should the earthquake occur near a high tide condition.

GROUPS AND COMMITTEES ON SEISMIC HAZARD IN THE FRASER DELTA

FRASER SEISMIC TASK FORCE

Sponsored by:	City of Richmond
Concerned with:	Design of buildings in the Fraser Delta Geotechnical engineers - Co-Chairman Peter Byrne Structural engineers - Co-Chairman Nathan Anderson
Purpose:	Earthquake design in the Fraser Delta Final report completed, June, 1991

SEISMIC HAZARD IN THE LOWER MAINLAND

Sponsored by:	NSERC *Comprises a wide range of interest groups
Purpose:	Identify and rate geotechnical hazards - Chair: R.G. Campanella, UBC

GEOLOGICAL SURVEY OF CANADA

J. Luternauer
J. Clague
*Examine Geological Aspects:
Geology of the Fraser Delta
Geologic record of seismic activity shear wave velocity measurements

AMPLIFICATION IN THE FRASER DELTA

Sponsored by:	IRAP Klohn Leonoff UBC - Finn
Purpose:	Detailed study of possible amplifications in the Fraser Delta for incorporation in future Building Codes

SEISMIC EVALUATION OF PILES IN RICHMOND

Sponsored by:	B.C. Science Council McLeod Geotechnical - Naesgaard UBC - N. Anderson, P. Byrne
Purpose:	Field testing of piles in Richmond under simulated earthquake

FRASER DELTA: SEISMIC EVALUATION OF FOUNDATIONS FOR TRANSMISSION TOWERS - B.C. HYDRO

Concerned with:	Possible failure of foundations due to amplification and liquefaction

UBC RESEARCH GROUP - FRASER DELTA SEISMIC GEOTECHNICAL ASPECT

Byrne	- analysis and design
Campanella	- measurement of soil properties - in situ
Finn	- analysis and design
Vaid	- measurement of soil properties - laboratory

HAZARD ACCEPTABILITY THRESHOLDS FOR DEVELOPMENT APPROVALS BY LOCAL GOVERNMENT

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INTRODUCTION

Amendments to the Municipal Act in 1985 empowered and required local governments to address the question of geotechnical hazards in their development policies and permits. The wording of the legislation at the policy level speaks of "...designating areas... restricting the use of land ... [and] the protection of development from hazardous conditions ..." (Section 945). The Act states that development permits for new developments may "...specify areas of land that ... must remain free of development..." (Section 976) and that" ...where the geotechnical engineer ...determines that the land may not be used safely for the use intended, the building inspector shall refuse to issue the building permit." (Section 734). Basing their decisions on policies and designations in the community plan, and on reports from geotechnical engineers, it is the building inspector in the case of new construction and the approving officer in the case of new subdivisions who must ultimately determine what is acceptable or "how safe is safe enough".

The methodology employed by Fraser-Cheam Regional District to implement these provision of the Municipal Act has been reported elsewhere (Cave *et al.*, 1990). The procedure involves, first, the identification of potential hazards through overview, secondary and site-specific geotechnical studies which provide a characterization of each hazard in descriptive terms and in terms of its probability of occurrence. Risk estimation, or exposure to hazard, is the second step in the procedure and this is simplified somewhat by the fact that it is the risk to the aggregate community over a period of time which is important for decision-making rather than the (much lower) risk to any given individual. As well as a quantitative aspect, however, risk has a "qualitative" component which reflects the type of hazard. The occurrence of some hazards, for example, will normally provide adequate time to alert the population, thereby limiting the risk only to property damage rather than personal injury also, whereas other types of hazard will exhibit few preliminary signs to forewarn of danger. Again some hazards are associated with so-called "voluntary" risks whereas others expose people involuntarily (Pack and Morgan, 1988). Both these qualitative and the quantitative aspects of risk are important in assessing acceptability.

Once the engineer has characterized the hazard and quantified its occurrence and related risks, its acceptability to the regulatory authority will involve an evaluation of:

1) the type of risk;
2) the type of development; and,
3) any possible remedial or protective measures.

These factors are analyzed in the eight matrices shown as Figures 2 to 9 which are used in Fraser-Cheam to secure consistency in the development approvals process. These matrices all take the same form which is illustrated in the stylized "Hazard Acceptability for Development" Chart shown as Figure 1. This illustrates how developments which involve greater increases in land use density and those exposed to greater risks are less likely to be approved. Each of the matrices in Figures 2 to 9 relates to a different type of geotechnical hazard specified in the Act and the content of each cell reflects a judgement as to whether the risk is acceptable. In fact, this question of acceptability is not a simple black and white issue and the figure and tables show that there are at least five levels of acceptability implied by the regulatory responses ranging from outright refusal to unconditional acceptance (see Table 1).

THE GEOTECHNICAL HAZARDS

The following descriptions of geotechnical hazards focus upon those characteristics which most affect whether or not the risk of exposure is acceptable. The distinctions, therefore, are based on the effects of the hazards rather than upon strict geotechnical classifications.

INUNDATION BY FLOOD WATERS

Of those named in the Act, this is the hazard which threatens the greatest amount of development in Fraser-Cheam. In some areas, particularly along certain reaches of the Fraser, it is also the most benign of the hazards because it is predictable, rates of flow are relatively slow and depth and duration of flooding are moderate. Bank-full conditions are also less frequent on the Fraser than on the more volatile mountain tributaries. In other areas, the hazard is much greater. Those portions of the flood-plain known as "primary" flood areas, roughly equivalent to the flood channel itself, are to be avoided completely.

Table 1. Hazard-related responses to development approval applications.

1. Approval without condition relating to hazards.
2. Approval, without siting conditions or protective works conditions, but with a covenant including "save harmless" conditions
3. Approval, but with siting requirements to avoid the hazard , or with requirements for protective works to mitigate the hazard.
4. Approval as (3) above, but with a covenant including "save harmless" conditions as well as siting conditions, protective works or both.
5. Not approved.

MOUNTAIN STREAM EROSION AND AVULSION

The Chilliwack River, the Choquihalla River, and Silverhope Creek are notoriously volatile and wild tributaries to the Fraser on which settlements have been established. Others, such as Yale, Frosst, and Hallecks creeks are less well known but also have settlements built on the alluvial fans at their mouths. All of these are mountain streams with steep gradients and in flood they are extremely dangerous. They have enormous concentrated energy and erosion of the banks can occur rapidly where the channel is cut in alluvium, and there is constant danger of avulsion at high water in the flood-plain areas and on the depositional fan. Their speed of attack is such that they must be regarded as potentially life-threatening.

DEBRIS FLOWS AND DEBRIS TORRENTS

The threat from debris flows and torrents is virtually ubiquitous in Fraser-Cheam, associated as it is, with steep, unstable first and second-order drainages which can become choked with debris from erosion and vegetation. Fortunately the effects of these hazards are localized in that they do not extend far into the flatter reaches of the drainages, but they have great destructive power and may occur without warning.

DEBRIS FLOODS

The lower reaches of these first and second-order drainages, at the point where the debris torrent spreads out and releases its energy, are typically subject to debris flows which grade into debris floods. The former still carry sufficient energy and destructive power to be capable of causing serious damage to buildings and even to people under certain conditions, while the latter is a depositional hazard which will cause property damage and nuisance.

LANDSLIDES, SMALL-SCALE, LOCALIZED

The potential de-stabilization of steep slopes is a constant concern whenever development takes place on unconsolidated material. In fact, depending upon the physical and chemical properties of the soil and the amount of distribution of water, shallow slopes may be subject to landslip. The event may be sudden and rapid, or gradual and incremental, but the danger signs of future movement are usually evident before the event. In Fraser-Cheam, slopes susceptible to localized failure are common and they pose a constant threat to those living below.

SNOW AVALANCHE

For the most part, snow avalanche tracks do not reach down to the settled areas of Fraser-Cheam and these hazards tend to be of far greater importance to the maintenance of transportation routes than they are to the development approval process. At Hemlock Valley ski resort, however, snow avalanches do pose a constraint to subdivision and construction. In the avalanche run-out zones, in their lowermost reaches where most of the energy has already been spent, it is possible to engineer structures to withstand the lateral thrust of moving snow. For the most part, however, the hazard is one entirely to be avoided.

ROCK FALL

Rock fall hazard results from the dislocation of rock fragments or small blocks from a slope, usually because of mechanical weathering (freeze-thaw). For the sake of evaluating risk acceptability, rock fall can be taken to include the various forms of rolling rock hazard. It is distinguished, perhaps rather arbitrarily, from massive landslide hazard on the basis of its much more frequent occurrence and its very much more localized effect. There is usually evidence on the ground at the toe of a slope to indicate the extent of land potentially affected by rock fall. Geotechnical studies can define a "rock fall shadow area" susceptible to the hazard and planning regulations can ensure that development avoids the area.

LANDSLIDES, MASSIVE, CATASTROPHIC

Fraser-Cheam Region is the site of a number of ancient and some recent massive landslides. The best known is the Hope Slide which moved approximately 47 million cubic metres of material in 1965. Others have been studied in the Fraser Valley at Lake-of-the-Woods, Mount Cheam, and Katz. Of the surficial hazards, they are the least common, the least predictable and by far the most destructive.

THE TYPES OF DEVELOPMENT

In the face of these hazards, seven types of development application are distinguished in order to evaluate their acceptability. They are ranked in order of increasing intensity of land use, from a minor building repair to a major rezoning, reflecting corresponding increases in exposure to risk. The following brief description is written, for the sake of simplicity, from the residential perspective only.

MINOR REPAIR

In a policy sense, an application for a building permit to repair an existing building is one of the most difficult types to evaluate. The Municipal Act itself distinguishes such applications by exempting the applicant from the requirement to hire a geotechnical engineer to prove the site safe (Sec. 734.[2.1]). It does not, however, exempt the building inspector from the duty to refuse the permit if he already possesses a report which identifies the site as hazardous (Sec. 734.3).

Apparently, the intent of the Act in this respect is similar to its provisions respecting "non-conformity" of land use which essentially permit the non-conformity to continue for the life span of the business or the life-span of the building, whichever is the shorter. By discouraging permits for repairs in areas of known hazard, the Act is discouraging the extension of the life-span of those buildings which would not have been approved under modern regulations.

In reality, of course, the analogy with non-conformity only provides a perspective from which to view the general issue of buildings sited in unsafe areas. It does not provide all the answers to individual applicants who may have lived in their houses for many years and who want simply to repair a leaky roof or to install a safer fireplace. Blanket refusal of all such applications because of off-site hazards would be draconian indeed, particularly for those repairs which are really only stop-gap measures and which do not materially extend the life of the building. Therefore, at Fraser-Cheam a Board policy has been struck to the effect that if the nature of the hazard is not life-threatening, and if the cost of the repair is not greater than 25 per cent of the value of the building before repair, and if the owner will register a covenant against the title guaranteeing to effect protective measures against the hazard in future before any further construction is undertaken, then a permit will be available. (It should be noted that some types of repair costing less than $2000 do not require a permit under local bylaws.)

MAJOR REPAIR

A major repair is defined as one, in which the cost exceeds 25 per cent of the assessed value of the structure before repair. It is seen as having the effect of extending the life-span of the building and therefore of increasing the exposure to the hazard in the long term. For this reason permits are not generally available in the face of significant risk from geotechnical hazard until remedial or protective work is undertaken. However, if the cumulative probability of occurrence throughout the extended life-span of the building is small, as it may be in the case of some low frequency events, then this type of permit may be issued in Fraser-Cheam.

RECONSTRUCTION

In one sense, reconstruction is just a more complete form of "major repair" but it differs in two important respects. First, it provides the opportunity to relocate the building to a safer site on the parcel and thereby to lessen the risk. Secondly, it is the type of permit which fire insurance policies typically require to be available to validate the policy. Outright refusal, therefore, could render the site value of a residential parcel virtually worthless. Thus the significance of the availability of reconstruction permits far outweighs the numbers actually ever applied for or issued and these permits are usually a central concern at any public hearings dealing with hazard land management policies. In general, the larger the parcel the easier it is to meet protective siting restrictions and the more likely is a reconstruction permit to be issued.

EXTENSION

Whereas reconstruction may simply amount to replacement and may not increase the density of use, an application to increase the size of a building does imply an increased density of use and therefore a greater annual risk. Moreover while reconstruction may facilitate relocation, extension does not. Thus, a permit to extend a building in a hazardous area is often more difficult to secure than is a permit to reconstruct.

NEW BUILDING

The right to construct a new home on an existing vacant lot is the issue most frequently discussed in the context of the new legislation on hazards. It is, in a sense, the "acid test".

Denial of such a permit, in most instances, is tantamount to rendering the lot unsalable at anything like its former value and almost inevitably this leads to threats of legal action both against those who now deny the permit and against those who previously approved the subdivision. It also leads, just as inevitably, to claims that the owner should somehow be compensated by the government for the difference between the market value of the lot and the value which it could command were the hazard not present. Such reactions are natural and understandable responses to perceived financial loss. It is rarely appreciated, however, that the act of identifying the hazard neither creates nor materially alters the level of risk; it merely raises awareness. Equally, the act of refusing the permit does not cause the loss of value. It is the knowledge that the property is unsafe to live on which is the specific detriment to market value; the refusal of the permit is the consequence. Indeed, to grant approval to construct an unsalable building would be more likely to compound than to mitigate the financial losses of the land owner.

Fortunately, the number of occasions on which permits cannot be issued for vacant lots is very few. Recent subdivisions will not have been approved unless they contain a building site which complies with the new provisions of the Municipal Act and the Land Title Act. It is the older subdivisions which may have problems. Indeed, the very physical and site difficulties which have kept these older lots vacant in the past generally prove now to be the very reasons why the permit is refused under Section 734. From this perspective, again, the refusal causes no real loss of value now; instead, it serves only to confirm how unrealistic were the owner's former expectations of value. Less common is the possibility, whenever the time interval is long between subdivision approval and building permit application, that the state of geotechnical knowledge will have advanced and will have identified a hazard on a lot formerly certified as safe.

SUBDIVISION

The regulations which subdivision approving officers must administer respecting geotechnical hazards are embedded in the Land Title Act (Sec.86[1][c][v] and Sec.82). They are charged with the duty of ensuring that all new lots registered are suited "...to the use intended..." (Sec.82) and that they comply with all local government bylaws, thereby invoking the planning and building regulations discussed above. In addition, Section 82 requires the approving officer specifically to take into account whether "the land is subject, or could reasonably be expected to be subject, to flooding, erosion, land slip, or avalanche."

Together, these regulations ensure that adequate detailed site planning is undertaken and that each new lot is safe to develop. They are not intended, however, to dictate the basic patterns of density at which new development will occur. The designation of density, the principal regulatory determinant of land value, is supposed to be done through zoning based upon community plan policies. Then the subdivision approval process, which is administrative rather than political in nature, can concern itself with issues of site planning and layout. If the overall planning and approval system is operating properly therefore, the approving officer's impact on land value should not be great.

Nevertheless, the level of hazard acceptable for a new subdivision will tend to be less than for other types of permit application for two reasons. First, these lots are new and should comply fully with modern safety standards in the same way that new buildings have to comply with the Building Code even if their building sites are less than ideal. Secondly, the subdivision will increase density of use of land and the exposure to the hazard.

Some low degree of hazard, however, is generally acceptable even in new subdivisions for two reasons. One reason is that subdivisions are typically in the nature of infill or extension of existing development and this established development may already be subject to the same hazard. Also, the zoning and community plan density designations can be taken by the approving officer as a general indication that elected authorities have deemed that level of risk to be acceptable.

MAJOR REZONING AND COMMUNITY PLAN AMENDMENT

The distinction between development which is in the nature of infilling or extension and development which involves creating new communities and new patterns of growth on new areas of land, is one which is reflected in the distinction between subdivision applications and applications for major rezonings and amendments to the community plan.

The community plan amendment raises the question as to whether, in the long term, the community should grow in one direction, or on one type of land, or another. It confronts the issue of whether any degree of exposure to the hazard is necessary or unavoidable. In the case of these far-reaching policy decisions, which could seriously impact the community for hundreds of years to come, the level of acceptable risk should be very small indeed. Areas which are known to be hazardous should simply be avoided unless there are simple mitigative measures or no viable alternatives.

REMEDIAL AND PROTECTIVE MEASURES

Where the risk is considered unacceptably high, some action is necessary to mitigate the hazard or to reduce exposure before approval can be given. These actions fall naturally into two classes discussed below: 1) avoidance (*i.e.* exposure reduction); and, 2) protection (*i.e.* hazard reduction). Note that both purport only to reduce the hazard, or to change the probabilities. A third action, the granting of "waivers" to "save-harmless" the approving agency is an attempt to transfer liability for the hazard and this will also be discussed briefly.

AVOIDANCE MEASURES

Reduction of exposure to risk by simple avoidance is obviously the most desirable mitigative measure. Examples embodied in regulation include elevation of construction above a "flood construction level", set-back requirements from streams to avoid the hazard of erosion and the primary flood area, and set-backs from the toe of a slope to avoid a rock-fall hazard or from a watercourse to avoid a debris torrent hazard. More complex techniques, such as slope stability monitoring devices coupled with warning and evacuation programs, have only rarely been employed in Fraser-Cheam for institutional reasons, but they do seem to offer promise in the future for those hazards which may affect communities already established.

At the policy level, simple avoidance is the preferred technique for official plans and zoning bylaws. Land can be designated for uses which minimize exposure to the hazard such as daytime summer tourist commercial uses in areas which are exposed to winter debris flow hazards, or industrial storage uses in areas which may have low probability rockfall hazard. From a technical perspective, it is worth noting that the Municipal Act encourages the use of the Development Permit regulations to implement such risk avoidance policies even to the point of allowing the permit to over-ride the use and density variations in the zoning bylaw.

PROTECTIVE MEASURES

Protective measures are more visible and generally more popular than regulated avoidance but they are less secure in their results and they usually involve a commitment to maintenance which is more difficult to achieve. In Fraser-Cheam the most common examples are rip-rap protection of river banks to prevent erosion and raised re-enforced foundations to protect against debris floods. Others include various types of protective berms and dykes designed to protect the immediate area against flooding, debris floods, rolling rock etc. and various forms of traps, grizzlies and debris basins designed to protect downstream areas from similar hazards.

TRANSFERENCE OF LIABILITY

One of the most common arguments relating to development applications in hazardous areas is whether approval can be granted in return for some form of waiver of the right to sue the regulatory authority in the event that damage or death occurs. This is usually coupled with some form of indemnity to protect the regulatory authority against suits launched by others. Such waivers are known as "save-harmless" covenants and, if linked to land use restrictions, can be registered as legal incumbrances against the title of the property pursuant to Section 215 of the Land Title Act.

It should be noted that these covenants are in the nature of private agreements between the landowner and the government. Thus third parties, such as visitors to the property, will be exposed involuntarily to the hazard while not being party to the agreement. Their statutory rights to protection cannot be transferred by these agreements.

Nevertheless, these covenants do serve a valuable function as an instrument on title, by informing prospective purchasers of known hazards. They may also have value, in some cases, as an attempt to recognize and assign the residual liability after all reasonable remedial and protective measures have been undertaken. They do not, however, provide an alternative to implementation of the requirements of the Municipal Act and the Land Title Act by elected officials, planners, building inspectors and approving officers. The duties of each are rather clearly spelled out in the statutes, and no private agreements or covenants can over-ride these obligations.

THE ACCEPTABILITY OF RISK IN FRASER-CHEAM

Table 1 lists the range of regulatory responses to development applications. These are the numbers in the individual cells in Figures 2 to 9. In practice, this spectrum from unconditional approval to outright refusal is far more complex and subtle than this list implies because each individual case confronts different specific hazards and presents different mitigative opportunities.

There are few generally accepted yardsticks which can provide help in calibrating regulatory approvals charts like those in Figures 2 to 9. One such yardstick derives from the Provincially sponsored flood-proofing program which provides financial support for protective measures and regulatory control over many forms of development. The design event for this program has a return frequency of once-in-200-years. Floods greater than this are regarded as too costly to protect against, too unlikely, or both; lesser floods are seen as too frequent and costly to be acceptable.

A second yardstick can be inferred from Provincial policy on subdivision approval in hazardous areas where advice is given to geotechnical engineers "...to think in terms of a 10 per cent probability [of occurrence] in 50 years..." (*i.e.* 1:500 annually). This appears to be an appropriate standard for infill or extension subdivision or for rezoning.

A third guideline derives from the B.C. Supreme Court decision of Mr. Justice Berger in 1973 which found a site exposed to a very low probability of landslide occurrence (1:10 000) to be unsuitable for development (Berger, 1973). In this case, the development would have formed the nucleus of a new community while the suspected hazard was a type of massive and destructive landslide. Thus it provides a solid precedent for broad community planning policy. A 1:10 000 probability is assigned to an event the occurrence of which, though apparently possible at any time, has not taken place within the last 10,000 years (*i.e.* not since the climatic change at the end of the last glacial episode). In this sense, the 1:10 000 standard has absolute significance in that such hazards have not occurred under existing climatic conditions. It may be the best practical definition of "safe".

Apart from these few guidelines, the other entries on the regulatory approvals charts (Figures 2 to 9) are all relative and subjectively determined. They are derived, as inevitably they must be, from experience in adjudicating numerous individual applications and from the constant search for consistency and for that elusive threshold of acceptability. Once compiled the charts are deceptively simple in their appearance. However, it must be emphasized that what is classified here, for example, simply as a "type 4" approval (see Table 1) in fact includes a wide variety of conditions both on the ground and in the covenant.

Nevertheless, together these charts comprise a public policy statement on development safety standards. As such, they are dynamic and will change as societal standards change and as scientific knowledge improves.

CONCLUSION

The principal value of a set of formalized approvals charts like those presented here is to facilitate consistent application of safety regulations and to permit comparison. Undoubtedly, these standards could be enforced with even conviction, and with more certainty of fairness, if they had been debated more generally and if a provincial consensus had already been achieved. For the future, and after the consensus is achieved, it is even possible to envisage a regulatory scheme analogous to the Building Code which already specifies standards for such hazards as earthquake, wind, snowloads, weak soils and fire-spread. There is no intrinsic reason why geotechnical hazards should not be included in the Code in the long term.

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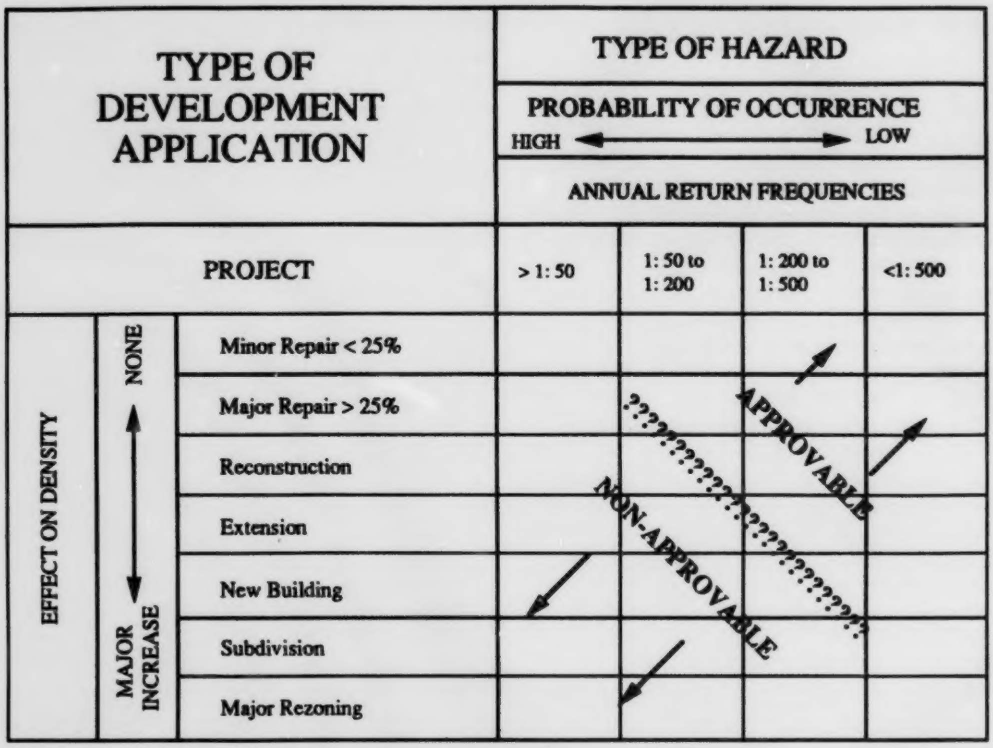
TYPE OF DEVELOPMENT APPLICATION
TYPE OF HAZARD
PROBABILITY OF OCCURRENCE
HIGH
LOW
ANNUAL RETURN FREQUENCIES
PROJECT
> 1: 50
1: 50 to 1: 200
1: 200 to 1: 500
<1: 500
EFFECT ON DENSITY
NONE
MAJOR INCREASE
Minor Repair < 25%
Major Repair > 25%
Reconstruction
Extension
New Building
Subdivision
Major Rezoning
APPROVABLE
????????????????????????
NON-APPROVABLE

Figure 1: Hazard acceptability for development.

INUNDATION BY FLOOD WATERS FROM FRASER RIVER & TRIBUTARIES				
	1:40	1:40 - 1:200	1:200 - 1:500	1:500 - 1:10 000
Minor Repair (<25%)	2	1	1	1
Major Repair (>25%)	4	3	3	1
Reconstruction	4	3	3	1
Extension	4	3	3	1
New Building	4	3	3	1
Subdivision (infill/extend)	5	4	4	1
Rezoning (for new community)	5	5	5	1

Figure 2: Inundation by flood waters.

DEBRIS FLOOD

	1:50	1:50 - 1:200	1:200 - 1:500	1:500 - 1:10 000
Minor Repair (<25%)	2	1	1	1
Major Repair (>25%)	4	3	3	1
Reconstruction	4	3	3	1
Extension	4	3	3	1
New Building	4	3	3	1
Subdivision (infill/extend)	5	4	4	1
Rezoning (for new community)	5	5	5	1

Figure 3: Debris flood hazard.

MOUNTAIN STREAM EROSION OR AVULSION

	1:50	1:50 - 1:200	1:200 - 1:500	1:500 - 1:10 000
Minor Repair (<25%)	2	1	1	1
Major Repair (>25%)	4	3	3	1
Reconstruction	4	3	3	1
Extension	4	3	3	1
New Building	4	3	3	1
Subdivision (infill/extend)	5	4	4	1
Rezoning (for new community)	5	5	5	1

Figure 4: Mountain stream erosion or avulsion hazard.

DEBRIS FLOW/DEBRIS TORRENT

	1:50	1:50 - 1:200	1:200 - 1:500	1:500 - 1:10 000	<1:10 000
Minor Repair (<25%)	4	2	1	1	1
Major Repair (>25%)	4	4	1	1	1
Reconstruction	5	4	3	1	1
Extension	5	4	3	1	1
New Building	5	4	3	1	1
Subdivision (infill/extend)	5	5	4	1	1
Rezoning (for new community)	5	5	5	1	1

Figure 5: Debris flow/debris torrent hazard.

SMALL-SCALE LOCALIZED LANDSLIP

	1:50	1:50 - 1:200	1:200 - 1:500	1:500 - 1:10 000	<1:10 000
Minor Repair (<25%)	5	2	2	1	1
Major Repair (>25%)	5	4	4	4	1
Reconstruction	5	4	4	4	1
Extension	5	4	4	4	1
New Building	5	4	4	3	1
Subdivision (infill/extend)	5	5	5	4	1
Rezoning (for new community)	5	5	5	5	1

Figure 6: Small-scale localized landslip hazard.

SNOW AVALANCHE

	1:30	1:30 - 1:100	1:100 - 1:500	1:500 - 1:10 000	<1:10 000
Minor Repair (<25%)	5	4	4	4	1
Major Repair (>25%)	5	4	4	4	1
Reconstruction	5	4	4	4	1
Extension	5	4	4	4	1
New Building	5	4	4	4	1
Subdivision (infill/extend)	5	5	5	4	1
Rezoning (for new community)	5	5	5	5	1

Figure 7: Snow avalanche hazard.

ROCKFALL SMALL-SCALE DETACHMENT

	1:100	1:100 1:500	1:500- 1:1 000	1:10 000- 1:10 000	<1:10 000
Minor Repair (<25%)	5	2	1	1	1
Major Repair (>25%)	5	4	2	1	1
Reconstruction	5	4	2	1	1
Extension	5	5	4	1	1
New Building	5	5	4	1	1
Subdivision (infill/extend)	5	5	5	4	1
Rezoning (for new community)	5	5	5	5	1

Figure 8: Rockfall small-scale detachment hazard.

MAJOR CATASTROPHIC LANDSLIDE

	1:200	1:200- 1:500	1:500- 1:1 000	1:10 000- 1:10 000	<1:10 000
Minor Repair (<25%)	5	2	1	1	1
Major Repair (>25%)	5	5	2	1	1
Reconstruction	5	5	5	1	1
Extension	5	5	5	1	1
New Building	5	5	5	1	1
Subdivision (infill/extend)	5	5	5	5	1
Rezoning (for new community)	5	5	5	5	1

Figure 9: Major catastrophic landslide hazard.

THE CONSULTANT'S ROLE IN RESIDENTIAL GEOTECHNICAL HAZARD INVESTIGATIONS IN BRITISH COLUMBIA

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ABSTRACT

Geotechnical consultants identify and map hazardous terrain and attempt to solve landslide problems. We are undertaking more studies of hazards which affect residential properties. This work has increased because of requirements for subdivision applications to the B. C. Ministry of Transportation and Highways (MoTH) and community building permit applications under the mandate of the B. C. Municipal Act.

Some studies involve active landslides but most require attention to conditional hazards which may pose minimal risk if they are anticipated with engineering advice or avoided. The work requires conservative engineering judgement and is becoming a specialized area of geotechnical practice.

Provincial standards require protection from a flood with a recurrence interval of 200 years. The design earthquake standard has a return period of 475 years. Landslides are unique (infrequent) events with no historic data that can be statistically analyzed to determine a return period.

Consultants may choose not to engage in residential hazard work because household budgets limit the possibilities of detailed investigations and there is much inherent liability. The geotechnical community is uncomfortable with wording in Section 734 of the Municipal Act which asks engineers to certify the safe use of land. If this wording is used in a report and an event occurs which results in a liability claim, insurers may disallow coverage.

Many liability concerns are overcome with estimates of relative probabilities of hazard occurrence and reference to a probability guideline for acceptable risk. A current guideline for determination of acceptable risk is given in a form letter to subdivision applicants by the MoTH. It is an annual probability of hazard occurrence equal to 1/500 or 0.002. The estimating process recognizes the reality of geologic and climatic uncertainty and improves understanding of the nature of hazard and risk.

Local elected officials should determine probability standards of acceptable risk of geotechnical hazards in their communities. The acceptable risk guideline deserves wider understanding if it is to be used as effectively. Its implications are discussed and comparisons are made with risks incurred in driving a car.

INTRODUCTION

Geotechnical consultants identify and map hazardous terrain and attempt to solve landslide problems. We have always undertaken landslide investigations for large civil works such as highways and railways. We are undertaking more studies of hazards which affect residential properties. This work has increased because of requirements for subdivision applications to the B.C. Ministry of Transportation and Highways (MoTH) and community building permit applications under the mandate of the B.C. Municipal Act. Provincial and municipal agencies are increasingly aware of geotechnical hazards and are concerned with development pressure on steep land or recurrent hazards in areas of established development.

This paper concentrates on landslide hazards and related risks to residential properties. The hazard occurrences are those which require a report...*by a professional engineer with experience in geotechnical engineering* (B. C. Municipal Act, 1979, Section 734.2, p. 211).

Our many case histories indicate the details of problem solving for residential hazards are surprisingly varied and complex. Neighboring properties are often involved unexpectedly.

Nonetheless, if home sites or rear yards were not inset into undercut slopes, if no fill (including yard litter) was dumped on any steep slope, and houses were located prudent distances from the top or base of any slope, Section 734 of the Municipal Act might be regarded as a curiosity.

The positioning of heavy exploration equipment such as drills and backhoes is often so severely restricted by unstable slopes, residential and forest features and adjacent private land that detailed investigations for individual houses may be infeasible.

Clients who endure harsh lessons in geology and refusal of a building permit are often small property owners whose land use may be partially constrained or entirely alienated by geotechnical reports. The marginal economic circumstances of these citizens make them least able to pay for expensive geotechnical services.

Important elements of this consulting work are engineering and geologic skills, balanced judgement, ethical considerations, clear written reporting and, more-of-late, lucid and trustworthy public forum explanations of the complexities of geotechnical hazards. Our experience indicates these elements are used to full advantage in Municipalities and Regional Districts where staff planners and building inspectors work cooperatively.

This paper begins its illustration of a consultant's role in a case where the municipal building inspector has the advantage of a reconnaissance geotechnical study to guide the resident, himself and a geotechnical engineer. Let us turn to an evening conversation between husband and wife somewhere in British Columbia.

TUESDAY EVENING AT THE GERATH HOME

Mr. Gerath comes home for supper and tells his wife that, at the request of the building inspector, he called a geotechnical company in Vancouver about the soil crack that appeared on the slope behind the house after the heavy rain last week.

"This character says he's worked in the area and he mentioned a report which says that landslides can be caused by lousy soil, too much water and undercut slopes right behind most houses along the street. I guess this report talks about landslide probabilities and he said something like 1 in 25 to 1 in 100 every year on our slope. I guess our slide could get bigger and might hit the house.

"I told him I don't understand how we can suddenly have a landslide because our house has been safe since your brother built it over 20 years ago. He says the danger has always been there but the law has changed. The town didn't have to approve building sites 20 years ago.

"He checked a map and said the slope is about 10 metres high and that the report has a landslide safe line running right through the back of the house. I told him our place is at least 50 feet from the bottom of the hill, we haven't cut any slope and we park our car and truck in the back yard. He said we might be okay if we have that much room".

"He said in the worst case we might have to clear out of the house for the time being. That's what happened to those people two blocks away -- he did their report. Maybe I should have told him the kid's rooms are at the back. Anyway, he estimates the cost of the visit and preliminary report will be $2500 including GST. Yeah, that's what I said".

"The engineer can't be sure his report will be favorable but he's hopeful. He'll let us know after he comes out but if he has to do more work, it will cost more to fix the problem. When I asked *how* much, he said it could be $2000 to $20,000 -- hard to tell. He's going to call the building inspector and he can come out Friday."

Mr. Gerath lit a cigarette. He turned to his wife and asked, "What's your brother's number?"

OVERVIEW STUDIES

Overview or reconnaissance studies are important means of determining the distribution and nature of geotechnical hazards. These studies acquire much geologic understanding and set the context of future, more detailed investigations. They determine where geotechnical precautions should be applied for planning and building permit issuance. They may be completed at several levels of detail with increasing focus on hazards which affect groups of homes (Cave *et al.*, 1990).

The studies use cadastral and topographic base maps of 1:5 000 scale which are available for many developed areas. A lack of detailed topographic mapping is a serious impediment in the completion of overview work and more detailed study. The work requires varying amounts of field work including foot traverses, slope measurements, soil sampling, aerial photo studies and interviews with local residents.

The costs of overview studies vary from about $10,000 to $50,000 depending on the severity of the terrain, the density of development and the extent of hazards. The Provincial government may provide planning grants to support geotechnical overview studies.

Consider the advantages of prior knowledge that an overview study has given the building inspector, the consultant and the Geraths. The inspector knows a study should be made and why, the consultant has a frame of reference for his cost estimate and Mr. Gerath recognizes the context of the hazard and its possible conditional nature.

THE CONSULTANT'S ROLE

A geotechnical consultant is sometimes called to review a site after a landslide occurs or when there is alarming evidence of slope movement. In these cases, avoidance of property damage or injury may require drastic action such as abandonment of homes and expenditures of money beyond the resources of most households. It is interesting to note that when there is imminent landslide danger to a house, there is immediate justification for people to vacate. It is much more difficult and costly to determine the conditions under which they should return.

Most consultant commissions now involve sites where hazards are not obvious to less critical observers. These are marginal sites where conditional hazards may arise from incautious excavations, fills or drainage works. In these cases, the consultant must exclude a possibility of unconditional hazards such as a landslide or rock fall activity. He then determines if conditional hazards are possible and probable with the knowledge that well-intentioned property owners may bring disaster by incautious activity. [If a property owner has heavy excavating equipment in the back yard or a brother-in-law with the same, there should be an *unconditional* expectation that *conditional* hazards will be realized!].

As the evaluation proceeds, the consultant considers risks (or exposure to hazards) to both his client and himself. Among these are:

1) Professional judgement. Is a determination of hazard and probability based on realistic considerations? Is there historic or ancient evidence of landsliding in comparable nearby settings? Is he in general agreement with types of hazards and estimated probabilities given in an overview study if available?

2) What are the risks to the client if the hazard occurs? Is there a risk of property damage, injury or death? Can each of these risks be distinguished in any way that is useful?

3) Has the community matured with an official community plan and zoning bylaws (*e.g.* no dumping of fill without permits). Does the community have a knowledgeable and attentive planning and building department staff?

4) Does the client have the will and financial means to achieve a solution? Does the possibility of a solution justify an assumption of liability consistent with the anticipated fee value?

The last point is crucial in an understanding of the consultant's role. Unless large amounts of money are available to achieve an engineered solution, geotechnical advice regarding landslides in residential areas is always, in varying degrees, judgmental and conservative. This may be unsatisfactory to many engineers and scientists but it is a fact. Obviously the geotechnical consultants who engage in this work should have proven judgement. The greatest risk to all parties occurs when the consultant is wrong in a favorable assessment, not when he is right in an unfavorable one.

WORDING OF THE MUNICIPAL ACT

The Municipal Act states (hazards) ...may require a report *certified by a professional engineer with experience in geotechnical engineering that the land may be used safely for the use intended*

(B.C. Municipal Act, 1979, Section 734.2, p. 211).

Errors and omissions Insurers may disallow coverage in instances where statements such as "certified safe" are made in relation to geotechnical hazards. It is ironic that increasing liability concern has unexpectedly led to engineers' discomfort over the very wording which mandates our work in the field.

Liability insurance protects consultants from ruinous claims. It is very expensive and a major portion of the overhead expenses of geotechnical companies (see H.W. Nasmith, 1986). Furthermore, the deductible limit is high -- perhaps on the order of $50,000 per claim.

Any geotechnical consulting firm is wary of liability claims. The potential for such claims accumulates and the profit on 20 or more projects may be expended on the deductible for one claim and an increase in annual premiums. This explains why engineering advice on residential hazards is conservative and why we decline involvement in some cases.

At this point, it is important to make a positive statement: The Municipal Act recognizes the reality of geotechnical hazards and requires land owners to do the same. Even in settings where hazards were unrecognized, our experience indicates most geotechnical reports for building permit applications show property owners how to avoid or minimize their risks.

HAZARD OCCURRENCE

Flood occurrences are evaluated by statistical analyses of gauged stream flow records to give a flood return period (or recurrence interval). The return period is the average interval of time within which a given occurrence will be equaled or exceeded. In British Columbia, the design flood has a return period of 200 years. It is a discharge from which extreme water levels are derived to plot a flood plain limit. Extreme water levels do not deal directly with attendant and varying probabilities of property damage, injury or death within the flood plain. These probabilities depend on variables such as structural integrity, occupancy, on local current velocity and erosive power, sediment transport and the impact of floating debris.

In the reality of engineering practice, any flood occurrence is treated as though it generates equal risks of property damage, injury and death. The probabilities of injury or loss of life, or *total risk*, are implied but not calculated.

Provincial standards require protection from a flood with a recurrence interval of 200 years. The design earthquake standard has a return period of 475 years. Landslides are unique and infrequent events with no historic records that can be statistically analyzed to determine a return period.

A geotechnical engineer assesses landslide occurrences with variable and often incomplete diagnostic evidence which may include observations of ancient landslide scars, measured slope angles, approximations and assumptions about geologic materials and hydrologic conditions, observations of thrown trees and considerations of possible triggering events such as rain storms or sudden thaws.

Even if the engineer is willing to report that a property can be used safely, he cannot do so unless he somehow makes a *relative* assessment about an occurrence. At minimum, he has to estimate if there is a high, medium or low probability of hazard occurrence. His relative comparisons are based on his experience, knowledge of landslides in similar settings and preferably the nearest historic landslide with a similar physical setting.

Graham Morgan (1992) and Peter Cave (1992) point out that logical evaluations of risk and determinations of risk acceptability require *estimations of annual probabilities of hazard occurrences*. There are significance advantages in logic and clarity of understanding if hazards are evaluated this way.

The consultant ties his relative assessment to a time frame to make a probability estimate. A high probability of occurrence might mean estimated certainty of landsliding within the next year and range to an estimated 100 percent probability within the next 100 years. A medium probability of occurrence might mean an estimated certainty within the next 100 to 500 years and a low probability may mean an estimated certainty within 500 to 1000 or more years.

These qualitative time-related assessments require considerable experience and careful observation. For instance, the consultant may observe that a slope has no evidence of landsliding within the 10,000 years since deglaciation. He may estimate the minimum age of earth slumping from a cluster of upright 60 year old trees on a slump block while observing that a property owner has excavated the toe of the slump. He may know a damaging debris torrent was triggered by a 1 in 50 year rain storm occurrence five years ago.

It is not always possible to estimate occurrence probabilities from available evidence. In such cases, a consultant may recommend drilling and other investigations with substantial additional costs and no more assurance of a favorable outcome for a property owner.

Obviously, a probability estimate may not be necessary if there is an imminent risk of landslide damage or worse. The estimate may be highly important when it is time to weigh the risk of reoccupying or relocating an intact house. The engineer can estimate a range of annual probability and qualify the estimate of occurrence in any way.

The estimation process should lead to internally consistent analyses and reporting. Every report on residential geotechnical hazards should be prepared to a standard which anticipates critical engineering reviews of lines of judgmental reasoning as well as technical information. The estimate of probability of hazard occurrence does not have to be certifiably correct but, given geologic and climatic uncertainty and an understanding of risk, it should be reasonable and defensible.

ESTIMATED RELATIVE PROBABILITY OF OCCURRENCE

The estimated relative probability of hazard occurrence is the first factor in a theoretical calculation of risk. The risk of property damage, injury or death should, in principal, always be less than the occurrence probability because of the reciprocal nature of the multipliers. For example, suppose a slope above a summer cottage has an estimated annual probability of landslide occurrence of 0.01 or 1/100 annually. If the cottage is to be occupied for 1/4 of the year, the projected theoretical annual probability of resident exposure to hazard is 0.25. If the occurrence probability is multiplied by the exposure factor, the theoretical probability of resident injury or death is 0.0025 or 1/400 annually.

It is again time to return to reality of geotechnical practice. As long as a landslide can reach areas of daily recreation and habitation, estimates of hazard occurrence *are given (and taken) as statements of the total risk*. This is conservative practice and consistent with evaluating other hazards such as floods. The practice allows for uncertainty including that of the basic factor, the occurrence probability.

It is important to note that calculations of total risk are useful in considerations of contingent action (house evacuation during heavy rain storms), changes in life style (no play in the back yard behind the driveway) and landslide run out behaviors with significantly reduced landslide risks. Total risk calculations are also very useful in considering effects of large landslides with low probabilities of occurrence.

WEIGHING THE RISK

Provincial standards require protection from floods and earthquakes by recurrence interval standards. There is no comparable standard for landslide avoidance or protective works. Although engineers can estimate probabilities of occurrence they should not, as individuals, set standards for acceptable landslide risks any more than they do for floods and earthquakes.

The British Columbia Ministry of Transportation and Highways (MoTH) suggests an annual probability of occurrence equal to 1/500 (or 0.002 annually) as a guideline for a geotechnical evaluations of acceptable risk in the process of subdivision applications (Appendix A).

A 1/500 annual probability of occurrence is equivalent to a 99.8 per cent annual probability of non-occurrence. However, if the estimated hazard probability is used as a predictive index, there is a 5 per cent chance that the hazard will occur in the next 25 years and a 10 per cent chance that the hazard will occur in the next 50 years.

Standards of acceptable risk for planning and building permits may vary according to whether the development is new or existing or on the type of development such as school or commercial storage (Cave *et al.*, 1990; Cave, 1992).

Projected annual driver risks are useful indices for comparison with projected risks of landsliding (see Morgan, 1986; Pack and Morgan, 1988).

Driver risks are chosen because most people can relate to them; they have proven especially useful in public discussions of the nature of hazards and risk. Appendix B is a table of probabilities for car drivers in British Columbia for the year 1988 (Province of British Columbia, 1988). Item 5 in Appendix B is the MoTH Guideline for "acceptable" landslide occurrence.

The guideline for acceptable landslide risk is 20 times *less* likely the probability of car damage and about 7 times less likely than driver injury. It is about 20 times *more* likely than being killed while driving a car. This balance of probabilities suggests an annual probability of 1/500 is a reasonable guideline for acceptable risk.

We believe local elected officials should determine probability standards of acceptable risk for geotechnical hazards. They should be guided by Provincial criteria and can draw on experience of other municipalities, geotechnical consultants, citizens of the community and social and economic circumstances.

In the absence of local guidelines, it is possible for the engineer to express his understanding that his estimated probability does (does not) meet the current MoTH guideline for acceptable risk.

WHAT OF THE GERATHS?

The engineer assured the Geraths about living in their house. He recommended the soil crack be covered with plastic sheeting to prevent surface water infiltration and that the slope be visually monitored by Mr. Gerath and the building inspector. The engineer's evaluation of slope geometry and probable geologic conditions indicate the probability of a significant earth slump landslide is very high, perhaps in the range 1/1 to 1/50 annually.

The engineer assumes a slide occurrence is certain within the year. If it occurs, the slide mass run out is constrained by slope geometry, constituent soils, and other factors so it is likely to stop movement within 6 metres of the base of the slope. The engineer recommends leaving the geotechnical safe line at the rear of the house 14 metres from the base of the slope. He says this line contains the approximate limit of landslide run out with an estimated probability of occurrence of 1/500 annually (8 metres from the base of the slope plus a safety buffer of roughly 6 metres).

He makes several recommendations for land use such as restricting a back yard play area and contingencies for landslide clean up and repairs. He suggests several alternative schemes which will significantly decrease the medium to high probability of landslide deposition in the back yard.

CONCLUSION

There are significant advantages in logic and clarity of understanding if a consultant estimates relative probabilities of hazard occurrence and refers to a probability guideline for acceptable risk.

Consultants may choose not to engage in residential hazard work because household budgets limit the possibilities of detailed investigations and there is much inherent liability. The geotechnical community is uncomfortable with wording in Section 734 of the Municipal Act which asks engineers to certify the *safe* use of land. If this wording is used in a report and an event occurs which results in a liability claim, insurers may disallow coverage.

The Municipal Act recognizes the reality of geotechnical hazards and requires land owners to do the same. Even in settings where hazards were unrecognized, most geotechnical reports for building permit applications show property owners how to avoid or minimize their risks.

ACKNOWLEDGEMENT

I wish to thank Kirsten Pedersen of the Motor Vehicle Branch of the B. C. Solicitor General Office for her assistance in providing automobile accident statistics. Dr. Robert T. Pack of Terratech Consulting Ltd. and Dave Smith of Thurber Engineering made several helpful suggestions to improve a draft version of the test. I also thank my colleague, Dr. Oldrich Hungr for his many insights. Working Group B6 at the Geologic Hazards Workshop (February 20, 1991) sharpened my focus on several issues. I also thank Dr. Peter Cave, Hugh Sloan, Brenda Hartley and others at the Regional District of Fraser-Cheam who deal with more than a fair share of landslide hazards and have guided our practice.

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APPENDIX - A

Province of British Columbia

Ministry of Transportation and Highways

Proposed subdivision of

Your proposal for a ______________ lot subdivision has *not* been given approval by the Ministry of Transportation and Highways for the following reasons:

The Approving Officer believes that a geological hazard exists and it does not appear on the face of it, in the public interest to approve the proposal as submitted for the land use intended, because of the possible hazard to persons and/or property.

The Approving Officer's belief that the land is subject to geological hazard is based on a reconnaissance only. If you wish to explore this aspect further you should engage a Professional Engineer experienced in geotechnical engineering to advise you. He may, or may not, be able to recommend portions of the land for development, subject in some cases to permanent protective works. You should note that in many cases works are not economic and indeed can often cost more than the total development is worth. A full study is itself a certain expense, and if you do decide to explore this further, it may be prudent to engage him to do a preliminary overview study first in order to see whether it is worth going to a full study. Such a preliminary study would likely include a review of air photos, regional reports on surficial geology, contour maps, etc., and may not always need a site visit. If you then believe it is worth proceeding with a full study you should ask him to identify the nature, extent and probable frequency of the hazard or hazards, and to recommend permanent protective works, or detailed building lines, etc. It is difficult sometimes to quantify the frequency of occurrence of hazards but he should be asked to think in terms of a 10% probability in 50 years. If he has questions regarding terms of reference please ask him to contact me to discuss. Please supply four copies of any reports.

Ministry of Transportation and Highways

APPENDIX - B

TABLE OF COMPARATIVE RISKS * (Numbered items are in decreasing order of probability)

			PROJECTED RISK:	
	HAZARD	ANNUAL	25-YEAR	50-YEAR
1.	AUTOMOBILE DAMAGE WHILE DRIVING	1/25 (1/25 x 1/3.2 equals:)	100%	N/A%
2.	DRIVER INJURY	1/80 (1/80 x 1/2.5 equals:)	31%	62%
3.	DESIGN FLOOD OCCURRENCE	1/200 (1/200 x 1/2.38 equals:)	12.5%	25%
4	DESIGN EARTHQUAKE OCCURRENCE	1/475 (1/475 x 1/1.05 equals:)	5.3%	10%
5.	"ACCEPTABLE"	1/500 (1/500 x 1/20.2 equals:)	5.0%	10%
6.	DRIVER DEATH LANDSLIDE OCCURRENCE	1/10100	0.3%	0.6%

* Automobile and driver statistics based on 1988 records available from the Motor Vehicle Branch of the B.C. Solicitor General. Automobile accident data are rounded to facilitate comparisons and should be treated as reasonable approximations for comparison purposes only.

VOLCANIC HAZARDS AND VOLCANISM IN THE CANADIAN CORDILLERA

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ABSTRACT

British Columbia and the Yukon encompass a geologically dynamic region which includes subduction zones, areas of crustal rifting and high heat flow. As a consequence of this dynamic environment, some 100 volcanoes and volcanic fields have formed. These are arranged in five broad belts: the Garibaldi, Anahim, Alert Bay, Stikine, and Wrangell volcanic belts; plus other less-well-defined volcanic regions. Volcanoes range from monogenetic mafic cinder cones, to peralkaline shield volcanoes, and calc-alkaline strato-volcanoes. Determining the age of an eruption is sometimes difficult, but it is thought that the Tseax River Cone, in northeastern British Columbia, erupted about 200 years ago and is Canada's youngest volcano. The most recent large explosive eruption occurred 1300 years ago in the Yukon. The eruption, from a vent just inside the Alaska border, expelled an estimated 30 cubic kilometres of pyroclastic material covering 300,000 square kilometres of Yukon under a blanket of ash. The decimation of the environment triggered the migration of the ancestral Athapaskan Indians. In southwestern British Columbia, the most recent volcanic event is thought to be a plinian eruption from Mt. Meager strato-volcano about 2300 years ago which spread ash across southern British Columbia into Alberta.

The tectonic forces that produced these volcanoes are still active and the potential for a volcanic eruption in the Canadian Cordillera continues to exist. Much remains to be done to correctly assess the risk of a volcanic eruption in the Cordillera due to numbers and remoteness of volcanoes, and limited funding and personnel. Studies to date, suggest that small localized basaltic eruptions producing tephra that covers limited areas, and more infrequent violent explosive events, severely impacting vast areas are both possible. Basaltic eruptions may occur with little or no warning, but will only pose a hazard if the eruption occurs close to a populated area or a transportation corridor. Explosive eruptions usually have associated earth tremors that will be picked up on the regional seismic network. Unfortunately, however, some significant events elsewhere in the world have occurred where precursor seismicity commenced only hours before the volcano erupted explosively.

Apart from the hazard posed by an eruption of a Canadian Volcano, a continuing hazard is posed by the extreme relief of many vent areas and the unstable nature of volcanic deposits. Landslides and debris flows from volcanoes pose a very real threat. Comparable debris flows generated in volcanic areas have much greater run out distances than those generated in nonvolcanic areas, in part, because of a greater percentage of fine material in "volcanic" debris flows. Where human development is pushed into volcanic areas, this hazardous aspect of Cordilleran volcanoes must be taken into consideration during planning. Should an eruption occur, the impact would be much wider reaching.

INTRODUCTION

Volcanoes are a focus of fear and fascination. Here nature's power is unleashed; power we can stand and view, power to destroy and power to alter this entire planet. This paper reviews hazards posed by volcanoes in general and what we might expect from an eruption in Canada. Canada has been spared the almost ceaseless volcanism characteristic of such places as Hawaii, Japan, or Indonesia, but it has not escaped completely. We are part of a continuous line of subduction zones and transform faults that encircle the Pacific Ocean. Our global position on this dynamic sphere gives rise to not only subduction zone volcanoes, but to volcanoes formed where the crust is weakened and stretched by extension, and additionally by plumes in the underlying mantle creating upwelling of hot mantle material. These forces have produced five broad belts of volcanoes plus other less-well-defined volcanic regions (Figure 1). The Garibaldi and Wrangell volcanic belts owe their origin to subduction; the Stikine Volcanic Belt to crustal

Table 1. Volcanic hazard summary (modified from Blong, 1984, Table 1.4, page 12).

VOLCANIC HAZARD	<10	10-30	30-100	100-500	500-1000	>1000
	Frequency of Adverse Effect/Damage/Death Distance (kilometres)					
Lava flows	F	C	VR			
Ballistic projectiles	C					
Tephra falls	VF	F	F	C	R	
Pyroclastic flows and debris avalanches	A	F	R	VR		
Lahars and jokulhlaups	F	F	R	VR		
Seismic activity and ground deformation	C	C	VR			
Tsunami	A	F	C	R	VR	
Atmospheric effects	C	C	R	VR	VR	
Acid rains and gases	F	F	R	R	VR	VR

* Hazard level is based on the relative frequency of deaths given that the specific type of activity occurs. A = Always; VF = Very Frequent; F = Frequent; C = Common; R = Rate; VR = Very Rare.

Table 2. General relationships between volcano types, predominant lava, eruption styles, and common eruptive characteristics (from Tilling, 1989, Table 1.1, page 2).

VOLCANO TYPE:	Shield[1]
COMPOSITION:	Basaltic (mafic)
RELATIVE VISCOSITY:	Fluidal
ERUPTION STYLE:	Generally explosive to weakly explosive
COMMON ERUPTIVE CHARACTERISTICS:	Lava fountains, lava flow (long), lava lakes and pools

VOLCANO TYPE:	Shield[1]
COMPOSITION:	Andesitic
RELATIVE VISCOSITY:	Less fluidal
ERUPTION STYLE:	Generally explosive but sometimes non-explosive
COMMON ERUPTIVE CHARACTERISTICS:	Lava flows (medium), explosive ejecta, tephra falls

VOLCANO TYPE:	Composite[2]
COMPOSITION:	Dacitic to rhyolitic (felsic)
RELATIVE VISCOSITY:	Viscous to very viscous
ERUPTION STYLE:	Typically highly explosive, but can be non explosive especially after a large explosion
COMMON ERUPTIVE CHARACTERISTICS:	Explosive ejecta, tephra falls, pyroclastic flows and surges and lava domes

NOTES

1) Generally located in the interior of tectonic plates ("intraplate") and presumed to overlie "hot spots," but also may occur in other tectonic settings (*e.g.*, Anahim Volcanic Belt, Galapagos, Iceland, Kamchatka).

2) Generally located along or near the boundaries of convergent tectonic plates (subduction zones); also called strato-volcanoes (*e.g.*, Cascade-Garibaldi Volcanic Belt, Wrangell Volcanic Belt).

extension, and the Anahim Volcanic Belt to a mantle plume or hot spot. Deep faults and crustal dynamics in other regions formed volcanic fields such as Wells Gray-Clearwater and other isolated cones, or cone fields, in British Columbia and the Yukon. But, what of the risk? Do these volcanoes pose a threat to our Society?

VOLCANIC HAZARDS

Volcanoes, when they erupt, produce a number of hazardous events (Table 1). What hazard will occur at which volcano will depend to a large degree on the composition of the erupting magma (Table 2). Basaltic eruptions [basaltic magmas are low in silica, an essential building block element of minerals] pose a minimal hazard in comparison with explosive felsic eruptions [felsic or the older term 'acid' magmas are high in silica]. Similarly, an andesitic eruption is less hazardous than a dacitic one, but, a number of caveats must be applied. Basaltic eruptions occurring during winter months in regions of heavy snow pack could produce devastating debris flows (Lahars) or floods from rapidly melting snow. Some basaltic eruptions in Canada have been in mountainous terrain near glaciers. Subglacial volcanism has occurred in British Columbia in the past (see for example Mathews, 1942; Hickson, 1986; and others). This form of volcanism can produce potentially destructive jokulhlaups and water-magma interactions (phreatic or phreato-magmatic eruptions) can potentially produce very large explosions --- even if the magma is basaltic. Such an explosion, during the 1924 explosive phreatic event at Kilauea, caused the only recorded fatality of a Hawaiian eruption.

Hazards from the eruption of intermediate to high silica content magmas can be moderate to extreme - depending on the size of the eruption. The size of an eruption is quantified using a scale called the Volcanic Explosivity Index (VEI; Newhall and Self, 1982). The VEI takes into consideration the volume of eruptive products, height of eruption cloud, duration of the main eruptive phase, and other parameters to assign a number from a linear, 0 to 8 scale. The May 18, 1980 eruption of Mount St. Helens, which destroyed 632 square kilometres of land, expelled 1.4 cubic kilometres of magma (dense rock equivalent, DRE) and produced an eruption column which peaked at an elevation of 24 kilometres, had an VEI of 5. Table 3 gives a listing of the VEI of some noticeable volcanic eruptions in relationship to the loss of life. It can be seen that the actual size of the eruption does not have a direct relationship to the number of lives lost, however, it is directly proportional to the economic losses sustained by the region.

Modern man has never witnessed a truly cataclysmic eruption. The 1813 eruption of Tambora, ejected 50 cubic kilometres (DRE) of pyroclastic material into the atmosphere cooling the global climate by 2 °C for two years following the eruption. This cooling caused considerable hardship and famine in temperate areas of the northern hemisphere. We can only speculate upon the consequences of an eruption of the scale of Toba, Sumatra, which expelled 2500 cubic kilometres (DRE) of tephra and as a consequence may have brought about the last ice age (Chesner *et al.*, 1991).

VOLCANIC RISK

Erupting volcanoes only become a risk when there is something valued that may be destroyed - either lives, property or resources. Risk is usually assessed on the basis of the number of human lives which may be lost as a result of a hazardous event (Morgan, 1992). But, in actual fact, natural disasters throughout history have taken only a small fraction of the lives that have been lost in armed conflict. In 1000 years of record keeping, volcanoes have taken less than 300,000 lives (Tilling, 1989). The death toll from the recent Gulf War probably took at least a third that number of lives in just a few short weeks. Why then do we concern ourselves with the risk of death from natural hazards? The reason probably has more to do with the unexpectedness of the deaths and the belief that if more had been known or done, then perhaps, these lives could have been spared.

Yokoyama *et al.* (1984), devised a method for assessing risk of a volcano (Table 4). High risk volcanoes "score" 10 or above. Using this scheme and our present knowledge level, no Canadian volcano falls into the high risk category. Growing populations, however, increase the risk posed by volcanoes both here and abroad. For example, Mount Ruiz, Columbia, was not considered a high risk volcano, yet its eruption on November 13, 1985 killed 25,000 people - the greatest volcanic disaster since the eruption of Mount Pelee at the turn of the century. A poignant point brought out in Voight's (1990) retrospection of this event, was the observation that in 1845, a similar event wiped out 1400 people - all those that lived in the town

Table 3. Proposed criteria for identification of high-risk volcanoes (from Yokoyama *et al.*, 1984). A score of 1 is assigned for each rating criterion that applies; 0 if the criterion does not apply.

HAZARD SCORE *SCORE*

1) High silica content of eruptive products (andesite/dacite/rhyolite)
2) Major explosive activity within last 500 yr
3) Major explosive activity within last 5000 yr
4) Pyroclastic flows within last 500 yr
5) Mudflows within last 500 yr
6) Destructive tsunami within last 500 yr
7) Area of destruction within last 5000 yr is > 10 km^2
8) Area of destruction within last 5000 yr is > 100 km^2
9) Occurrence of frequent volcano-seismic swarms
10) Occurrence of significant ground deformation within last 50 yr

RISK RATING

1) Population at risk >100
2) Population at risk >1000
3) Population at risk >10,000
4) Population at risk >1 million
5) Historical fatalities
6) Evacuation as a result of historical eruption(s)

TOTAL SCORE

Table 4. Volcanic Explosivity Index (VEI) of Mount St. Helens and the deadliest eruptions since A.D. 1500 (modified from Tilling *et al.*, 1990, page 33).

Nevado del Ruiz, Colombia	1985	3	25,000
Mount St. Helens	1980	5	57
Mount Katmai	1912	6	0?
Mont Pelee, Martinique	1902	4	30,000
Krakatau, Indonesia	1883	6	36,000
Tambora, Indonesia	1815	7	92,000
Unzen, Japan	1792	3	15,000
Lakagigar (Laki), Iceland	1783	4	9,000
Kelut, Indonesia	1586	4	10,000

at that time. In 1985, 30,000 people now lived in the same area and repeat of the 1845 event resulted in an order of magnitude escalation in the loss of life. In a similar vein, the Philippine volcano of Mayon produced pyroclastic flows during its 1814 eruption which killed 1200 people - 800,000 people now live in the same area (Voight, 1990).

In Canada we are blessed with a country still relatively unpopulated so a volcanic eruption, with few exceptions, will probably result in no direct casualties (or at least very few). How then do we assess the risk if no lives are to be lost? How do we figure into our equations of risk the loss of a forest, of spawning streams, of a river, and of people displaced? These will be the legacy of any large explosive volcanic eruption in Canada.

PREPARING FOR AN ERUPTION

Despite infrequent natural disasters in Canada, we should not ignore the fact that we live in a tectonically active region in which future earthquakes and volcanic eruptions are a certainty. Peterson and Tilling (1991) have shown that countries experiencing many small eruptions are best able to cope with them, no matter what the economic status of the region. However, they find that countries faced with infrequent events, even when that country is scientifically advanced, have extreme difficulty dealing with volcanic events. "Unrest at long-quiescent volcanoes is particularly difficult to diagnose: such unrest does not necessarily culminate in an eruption, but if an eruption does occur, it may be particularly violent. Either outcome poses difficult challenges to scientists, not only in their study of the volcano, but in their public relations." (Peterson and Tilling, 1991).

Monitoring unrest at a volcano is a complex exercise that does not necessarily result in easy or straight forward answers. Figure 2 shows the relationship of scientists monitoring a volcano to a few of the groups that would become involved in any volcanic emergency. Communication between the groups and emergency planning are the key to effective response to a natural disaster.

Emergency planning is carried out in British Columbia by the Provincial Emergency Program (PEP) and Emergency Preparedness Canada (EPC). The responsibilities of both these agencies is outlined elsewhere in this volume (Dalley, 1992; Pollard, 1992). A critical review of emergency planning in British Columbia can be found in Anderson *et al.* (1990). At present, the level of preparedness for a volcanic eruption consists of a notification network set up between the agencies involved (Figure 3). Each agency has specific responsibility to pass information on to other involved agencies and to respond according to its individual mandate. In the case of Transport Canada, its responsibility will be to re-route aircraft away from the eruption and set up safe routes around the trouble area. PEP will be responsible for notification of the municipality and people living in the region affected. The Geological Survey of Canada (GSC) assumes responsibility for hazard warning (Appendix A), monitoring and passing information on to the other involved agencies as outlined in its 'Statement of Responsibility' (Appendix B). Assessment of potential volcanic activity will be handled by a committee called the 'Volcanic Activity Evaluation Committee' (VAEC). The guidelines and mandate of this committee are given in Appendix C.

At the present time it will be very difficult for the GSC to fulfill its role as outlined in the 'Agency Statement of Responsibility' (Appendix B). However, work is presently underway to identify sources of expertise and equipment which could be called upon to help in the case of a volcanic emergency. It will be the responsibility of the GSC Staff Volcanologist to make sure that these plans remain current and the interagency contacts kept up to date.

VOLCANIC THREAT IN SPECIFIC REGIONS

WRANGELL VOLCANIC BELT

The volcanoes in the Wrangell belt extend from southwestern Yukon into Alaska. The Belt, built over 25 million years ago, is related to subduction off the coast of Alaska (Stephens *et al.*, 1984) and is the eastern end of the historically much more active Aleutian Arc (Figure 4). The Wrangell belt is oldest in the east (Yukon) portion and becomes progressively younger westward into Alaska (Richter *et al.*, in press). Magma compositions span basalt to rhyolite fields, but andesitic lavas dominate. The most voluminous eruptive activity appears to have ended 200 000 years ago as the tectonic regime at the margin progressively changed from dominantly subduction to strike-slip movement (Richter *et al.*, in press). However, Holocene eruptions are known, the most significant of which were the "White River" eruptions from a vent just inside the Alaska border. The two eruptions were separated by several hundred years at 1800 and 1200 years before present, which ejected an estimated 30 cubic kilometres of material and covered 300 000 square kilometres of the Yukon with a blanket of ash (Figure 5) (Lerbekmo and Campbell, 1969). This eruption forced the migration of the proto-Athapaskan Indians into northern British Columbia and Alberta (D.W. Moodie written communication 1990). Some detailed work on the Wrangell belt has been carried out in Alaska (Richter *et al.*, in press), and more limited work in Canada (Skulski and Francis, 1986; Skulski *et al.* 1988).

STIKINE VOLCANIC BELT

The Stikine Volcanic Belt, consisting of over 50 Quaternary volcanic centres, extends northward from the Skeena River to the BC-Yukon border (Figure 1). This belt is related to crustal extension (Souther, in press) inboard of the region of transition from transform faulting to subduction along the North American-Pacific plate margin (Figure 4). Eruption of mafic to felsic alkalic magmas has produced strato-volcanoes, shield volcanoes and mafic cinder cones. Detailed mapping of two of the largest volcanic complexes in the Belt, Mount Edziza (Figure 6) (Souther, 1990, in press) and Level Mountain (Hamilton, 1981) have been carried out. Holocene eruptions in the belt are confined to small mafic cone building events. The Tseax River cone, at the southern end of the belt, erupted about 200 years ago (Sutherland Brown, 1969) and may be Canada's youngest volcanic eruption. Northward migration of the triple junction during the last 25 million years diminished extensional stresses in the region, likely reducing the possibility of future felsic eruptions. Mafic cone building events, taping deep magma sources, are still a possibility and their impact from an eruption on downstream habitation or installations must not be overlooked (Souther, 1981).

ANAHIM VOLCANIC BELT

The Anahim Volcanic Belt extends across central British Columbia from the coast to the Fraser River (Figure 1). Volcanism becomes progressively younger from west to east supporting the hypothesis that these volcanoes owe their origin to a mantle hot spot (Hickson, 1986; Souther, 1986). The belt consists of large alkalic shield volcanoes and small mafic cinder cones. Volcanism appears to have ceased in the western parts of the belts, but if the hypothesis is correct, future volcanism can be expected in the vicinity of Nazko Cone and east. Radiocarbon dating of Nazko Cone suggests that the last eruptive period was 7200 years BP (Figure 7) (Souther *et al.*, 1987). Future volcanism is most likely in the form of mafic cinder cones, but felsic eruptions, typical of the eastern portions of the belt, cannot be ruled out.

ALERT BAY VOLCANIC BELT

No Holocene eruptions are known in this group of volcanoes at the northern end of Vancouver Island (Figure 1) (Armstrong *et al.*, 1985) and volcanic activity has most likely ceased in the region.

GARIBALDI VOLCANIC BELT

The Garibaldi Volcanic Belt is the northward extension of the Cascade volcanoes. This chain of major andesitic to dacitic strato-volcanoes extends northward from northern California to British Columbia (Figure 4). The arc appears to be segmented (Guffanti and Weaver, 1988; Sherrod and Smith, in press); the central portion is the most active (Scott, 1990) and the northern end least active (Sherrod and Smith, in press). Scott (1990) tentatively identified periods during which the entire arc appears to have been active during the last 15,000 years. Long repose periods, up to several thousand years, between major explosive events at the major volcanoes (mounts Meager, Cayley and Garibaldi), appears to typify the Canadian portion of the arc. Mathews (1958) has also suggested there may be a causative link between glacial loading of the crust during ice ages and increased rates of volcanism in the Garibaldi belt.

A number of studies address volcanism in the Garibaldi Volcanic Belt. Among these are work by Mathews (1952, 1958), Green (1981, 1990), Souther (1980), Read (1978, 1990), and Stasiuk and Russell (1989, 1990). However, detailed physical volcanology studies have not been the principle focus of most of this work. Understanding eruptive processes and timing at individual volcanic complexes remains to be addressed. All of these studies have identified eruptive periods [an eruptive period is "a single eruption or series of eruptions closely spaced in time at a volcano .... that yield a preserved deposit and are differentiated from preceding and subsequent eruptive periods by one or more of the following criteria: (1) separated by an apparent dormant interval of decades to centuries, (2) distinguished by a change in vent location, and (3) marked by a distinct compositional change in eruptive products." Scott, 1990, p. 180]. These eruptive periods are compiled from Green *et al.* (1988 and references there in) and shown diagrammatically in Figures 8 to 11.

Volcanoes of the Garibaldi belt have been sporadically active over a time span of millions of years (Figures 8-11). The most recently documented eruption was about 2300 years BP at Mount Meager (Figure 12), 50 kilometres north west of Pemberton, may have been close in size to that of Mount St. Helens. Ash from this eruption can be traced as far east as western Alberta (Figure 5). This long history, coupled with continued subduction off the coast suggests we have not seen the last of volcanism in the Garibaldi belt. Hot springs in the vicinity of mounts Cayley and Meager suggests that magmatic heat is still present. Recent seismic imaging from the Geological Survey of Canada which supported Lithoprobe studies in the region of Mount Cayley, produced a 'bright spot' which may be attributable to a magma chamber at approximately 15 kilometres depth (R. Clowes oral communication 1990). These factors indicate we must be vigilant for signs of unrest at any of these volcanic centres.

In addition to possible future volcanic eruptions, the Garibaldi Volcanic Belt poses a considerable threat in the form of large rock failures (Evans, 1990; Clague and Souther, 1982; Read, 1981) and catastrophic debris flows (Jordan, 1990). The volcanoes are extremely rugged regions of high relief underlain by unstable, poorly consolidated and/or strongly jointed volcanic rocks. These conditions have already lead to a number of failures and debris flows. Comparable debris flows generated in volcanic areas have much greater run out distances than those generated in nonvolcanic areas, in part, because of a greater percentage of fine material in "volcanic" debris flows (Jordan, 1990). These factors must be taken into consideration before any development in the vicinity of the volcanoes.

OTHER REGIONS

Throughout British Columbia and the Yukon, isolated cinder cones and cone fields can be found. The most significant concentration of these is probably in the Wells Gray-Clearwater region of British Columbia. Volcanism over several million years has produced numerous small volume flows and cinder cones. The most recent of these, Kostal Cone (Figure 13) may be only a few hundred years old. These scattered, isolated cones and cone fields are unlikely to erupt again, but they do signify weaknesses in the crust which may preferentially channel the magma to produce more small volume mafic eruptions in the future. An exception to this is Volcano Mountain in the Yukon. This small mafic shield volcano and vents close by, have erupted several times in their one-two million year history, most recently early in the 19th century (L. Jackson oral communication 1990). It seems likely that future eruptions can be expected in this region as the volcanism is centered on the intersection of the Teslin Fault and another unnamed lineament.

CONCLUSIONS

British Columbia and the Yukon are blessed with some of the most spectacular scenery in the world - but we must not forget this scenery owes its origins to cataclysmic events in the earths interior. Uplift, mountain building, earthquakes and volcanoes are all part of our heritage. Although the Canadian Cordillera has been spared continuous volcanism on a human time frame - it has not on a geological one. We must try to look beyond the short recorded history of the human species when we are dealing with geologic hazards which have recurrence intervals longer then 50 years. Hazard zonation and planning must be an integral part of our future if we are to save lives and property. In the area of emergency planning for volcanic eruptions we can help by increasing public awareness and putting into place well thought out emergency plans. Detailed geological work at specific volcanoes that potentially threaten populations would help quantify the risk from future eruptions, rock failures and debris flows. This work should be carried out *before* rezoning or major shifts in population occur. We may not see an eruption in Canada in our lifetime, on the other hand we may - shouldn't we be prepared?

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APPENDIX - A

VOLCANIC HAZARD WARNING

The Geological Survey of Canada is responsible for monitoring and assessing the hazard potential of volcanoes in Canada. Some geologic events and seismic hazards are reported or monitored by the British Columbia Geological Survey Branch, University of British Columbia, B.C. Ministry of Environment, Lands and Parks, B.C. Ministry of Forests and other agencies/organizations. As the situation dictates, these agencies officially alert and warn appropriate agencies of increased or pending activity. This is considered to be the "formal" monitoring and reporting network.

The Assistant Deputy Ministry (GSC) will, on recommendation of the Scientist-in-charge and the Volcanic Activity Evaluation Committee, issue the following types of alerts or warning to other Federal and Provincial departments. Coordination of agency efforts will be through the Volcanic Emergency Response Plan - Canada:

Stage 1: Notice of Potential Hazard. Defined as "a general notice of potential hazard." This status applies to all volcanoes which are relatively young and could potentially be dangerous. These events may include volcanic phenomena (tephra fall, pyroclastic flows, lava flows), rock avalanches, debris flows and floods.

Stage 2: Hazard Watch. Defined as an "accumulation of sufficient information that indicates a potentially catastrophic event of generally predictable magnitude may occur within an indefinite period (possibly months or years)." This is recognition that something out of the ordinary is occurring.

Stage 3: Hazard Warning. Defined as a "prediction as to time, location, and magnitude of a potentially disastrous geologic event (possibly within days or hours)." This indicates the near certainty of an event. This designation requires a higher level of certainty which might not be attained early enough for formal issuances of a Hazard Warning through the VAEC by the Assistant Deputy Minister (GSC). In this case a warning, issued directly from the Scientist-in-charge (Cordilleran Division, GSC), will replace the formal published issuance of a Hazard Warning.

Additionally, the Scientist-in-charge (Cordilleran Division, GSC) may issue status reports and warning through telephone and other rapid communication links with operational agencies (see Volcanic Emergency Response Plan - Canada).

There is also an "informal" monitoring and reporting system that may be an initial source of unofficial warning information of an event in progress based on actual observation of volcanic activity. These sources include:

1) Transport Canada, Flight Service Centres, from pilot observations.

2) Provincial Emergency Program, field officers, and citizens.

3) Emergency Preparedness Canada, Field officers, and citizens.

4) Military installations, from pilot observations.

5) Atmospheric Environment Service, weather offices and weather stations

6) Area Residents, as citizens or as government workers "in the field" and training camps.

There will be a constant exchange to confirm information received and to obtain better, more specific situation reports between the Geological Survey of Canada and agencies in both the "informal" and "formal" reporting network.

APPENDIX - B

AGENCY STATEMENT OF RESPONSIBILITY

The main area of responsibility of the Geological Survey of Canada (GSC) during volcanic activity is to analyze volcanic and hydrologic hazards to permit informed decisions for Hazard Warning. The data required for these analyses will be obtained by:

1) basic geologic and hydrologic research to understand the nature of the volcanic events, and to interpret the event in terms of its potential danger; and,
2) monitoring in real-time, or nearly real-time, for continuing hazard analyses.

Basic research by GSC personnel will be coordinated by the Scientist-in-charge and integrated under his/her direction with studies by scientists in other government and academic institutions. The nature of these studies will depend upon the nature of expected eruptions and associated hazards.

Monitoring may include several areas of activity as outlined below:

1) **Observational Volcanology:** Make detailed observations of volcanic vent activity and the dispersal and deposition of the volcanic products; maintain a chronological written and photographic documentation of that activity.
2) **Seismology:** Coordinate activities with the Pacific Geoscience Centre to maintain a seismograph network to record seismicity related to the volcano, and to analyze the seismic data.
3) **Ground Deformation Studies:** Measure and record changes in the position and form of the surface of the volcano and its vicinity.
4) **Ejecta Studies:** Collect volcanic ash and other ejecta in volcanic eruptions and measure the features and properties of the deposits they form.
5) **Gas and Geochemical Studies:** Collect and analyze gases and condensed particles emitted by volcanic activity, principally by aerial methods but, if possible, by direct sampling at gas vents.
6) **Surface-Water Studies:** Measure changes in stream-flow and sediments in streams affected by runoff from the volcano, and analyze the chemistry of affected waters.
7) **Thermal Emission Studies:** Coordinate aerial infrared surveys and obtain additional thermal measurements, and make preliminary interpretations of the results in terms of volcanic processes.
8) **Emergency Geology Studies:** Examine the size and stability of source areas of potential mass movements, such as debris avalanches or mudflows.

The information collected in these investigations will be interpreted for input to Geological Survey decisions to issue hazards warnings and to provide information on the current status of the volcano for management decisions by other agencies.

APPENDIX C

VOLCANIC ACTIVITY EVALUATION COMMITTEE

MANDATE

To provide considered advice to the Assistant Deputy Minister (ADM), Geological Survey of Canada (GSC), Energy Mines and Resources on: 1) the scientific validity of the forecast or prediction of a volcanic eruption; 2) interpretation of specific activity which might be construed as precursor activity; and 3) appropriate response of the GSC to an event in progress.

In volcanology, forecasts and predictions are defined as:

Forecast - is a comparatively imprecise statement of the time, place, and nature of expected [volcanic] activity.

Prediction - is a comparatively precise statement of the time, place and ideally, the nature and size of impending activity. A prediction usually covers a shorter time period than a forecast and is generally based dominantly on interpretations and measurements of ongoing processes and secondarily on a projection of past history. (Swanson *et al.*, 1985*)

BACKGROUND

The President of the Privy Council and Minister responsible for Emergency Preparedness Canada (EPC) has indicated that officials of EPC will seek knowledgeable advice, as necessary from GSC, regarding volcanism, regional assessments of volcanic risk, forecasts and prediction of volcanic eruptions and appropriate response of government to actual volcanic events. To ensure that such forecasts or prediction will be carefully subjected to comprehensive review by qualified experts, the Assistant Deputy Minister (GSC) instructs the Director of the Cordilleran Division to form a Volcanic Activity Evaluation Committee (VAEC).

MEMBERSHIP

The Committee shall be composed of a Chairman, Vice-Chairman and no less than 8 or more than 15 members appointed by the Director, Cordilleran Division, with approval of the ADM (GSC) in consultation with the staff volcanologist (Cordilleran Division). Appointment shall be for a 5-year term except that the Chairman, the Director (Cordilleran Division), shall be ex-officio and the Vice-Chairman shall be the staff volcanologist (Cordilleran Division). Members shall consist of at least one Seismologist (Pacific Geoscience Centre). Other members shall be drawn from the GSC, Canadian Universities and foreign institutions undertaking discipline. At least one member or observer shall be appointed from the British Columbia Ministry of Energy, Mines and Petroleum Resources, Geological Survey Branch.

The Committee may request scientific experts as appropriate to participate in its discussions, in a non-voting capacity. Other individuals may be invited to participate as observers as determined appropriate by the Chairman or the Vice-Chairman.

Meetings may be called by the Chairman, Vice-Chairman, Seismologist or the ADM (GSC). Four voting members will represent a quorum provided at least two non-federal or provincial employees are present.

RESPONSIBILITIES

The Committee shall advise the ADM (GSC) on the scientific validity of a volcanic forecast or prediction, consequences or likely outcome of a volcanic event, the completeness of the available data and on related matters as assigned by the ADM. Specifically, the Committee shall be responsible for assessing forecasts or predictions of volcanic events and providing advice in a timely manner.

The ADM (GSC) shall be responsible for making information and the Committee's advice available to senior officers of Energy, Mines and Resources and Emergency Preparedness Canada for their action in informing other concerned agencies as necessary and appropriate. Such information and advice shall normally be pertinent to the possibility for the occurrence of a future potentially destructive volcanic eruption and will constitute the basis of a *Notice of Potential Hazard, Hazard Watch* or *Hazard Warning (Appendix B)*, and will be issued in accordance with the Volcanic Event Response Plan - Canada.

The Director (Cordilleran Division) will be responsible for; the administrative support of the

Committee and providing any necessary technical support required by it or any of its members, whenever they have been convened, in order for them to be able to evaluate any data put before it for consideration.

OBJECTIVES

In evaluating predictions or possible precursory activity, the Committee's objectives are:

1) to provide objective and critical review of the scientific data or interpretation of scientific data concerning the forecast or prediction of a volcanic eruption;

2) to recommend (to the appropriate scientist(s)) any actions that might be desirable or required to clarify or verify the forecast or prediction;

3) to maintain an accurate record of forecasts or predictions evaluated and evidence pertinent to them; and,

4) to provide ADM (GSC) a timely and concisely written review of the scientific evidence relevant to a forecast or prediction of any potentially damaging volcanic eruption and a written recommendation as to whether the evidence is sufficiently clear that official action should be taken. The report should include the full range of viewpoints expressed by Committee members. When time is of the essence, the written documents may follow oral presentation to the ADM (GSC).

FUNDING

Members of the Committee other than federal and provincial employees shall be re-imbursed for travel and per diem expenses only. Such expenses shall be provided by the Cordilleran Division (GSC).

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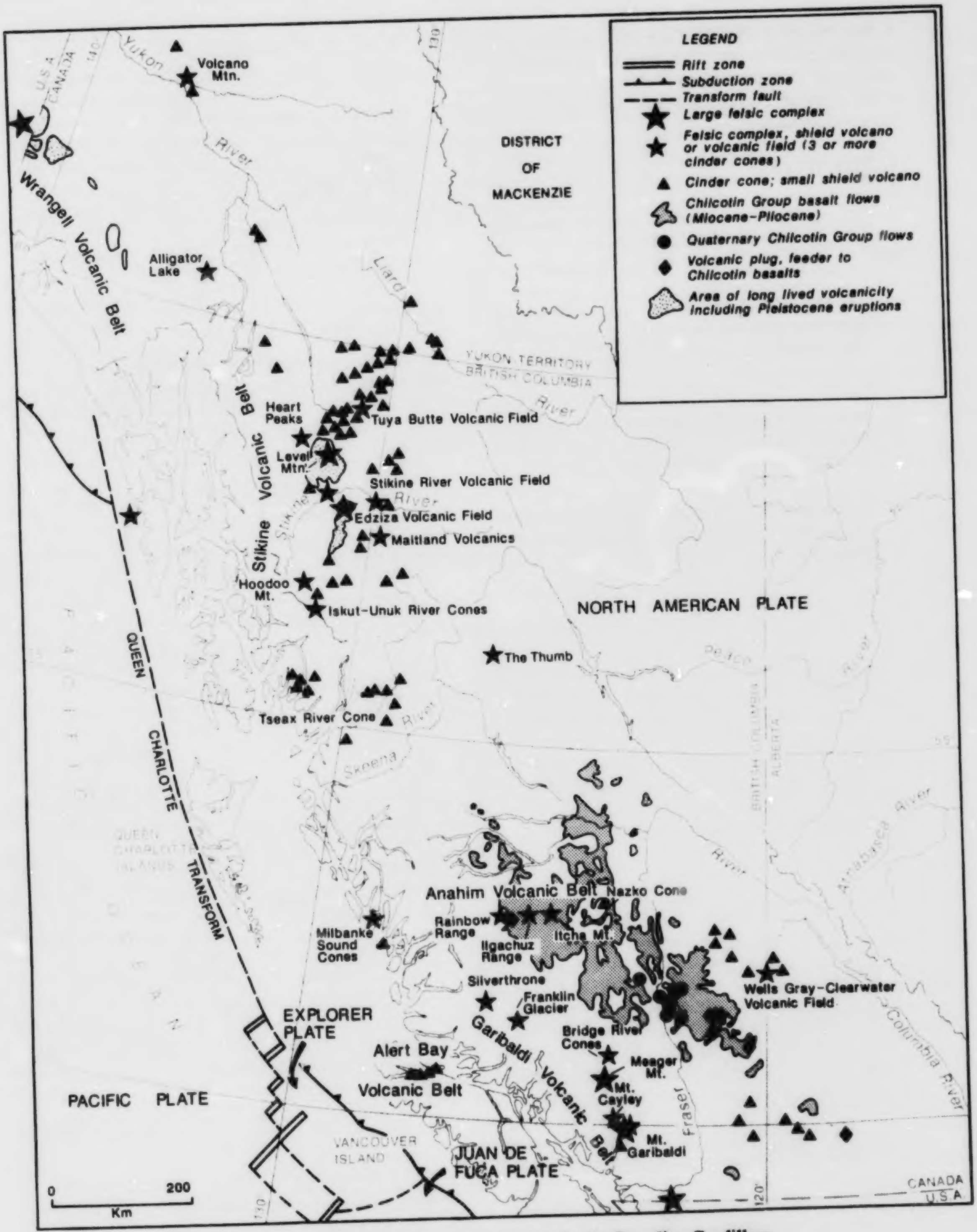
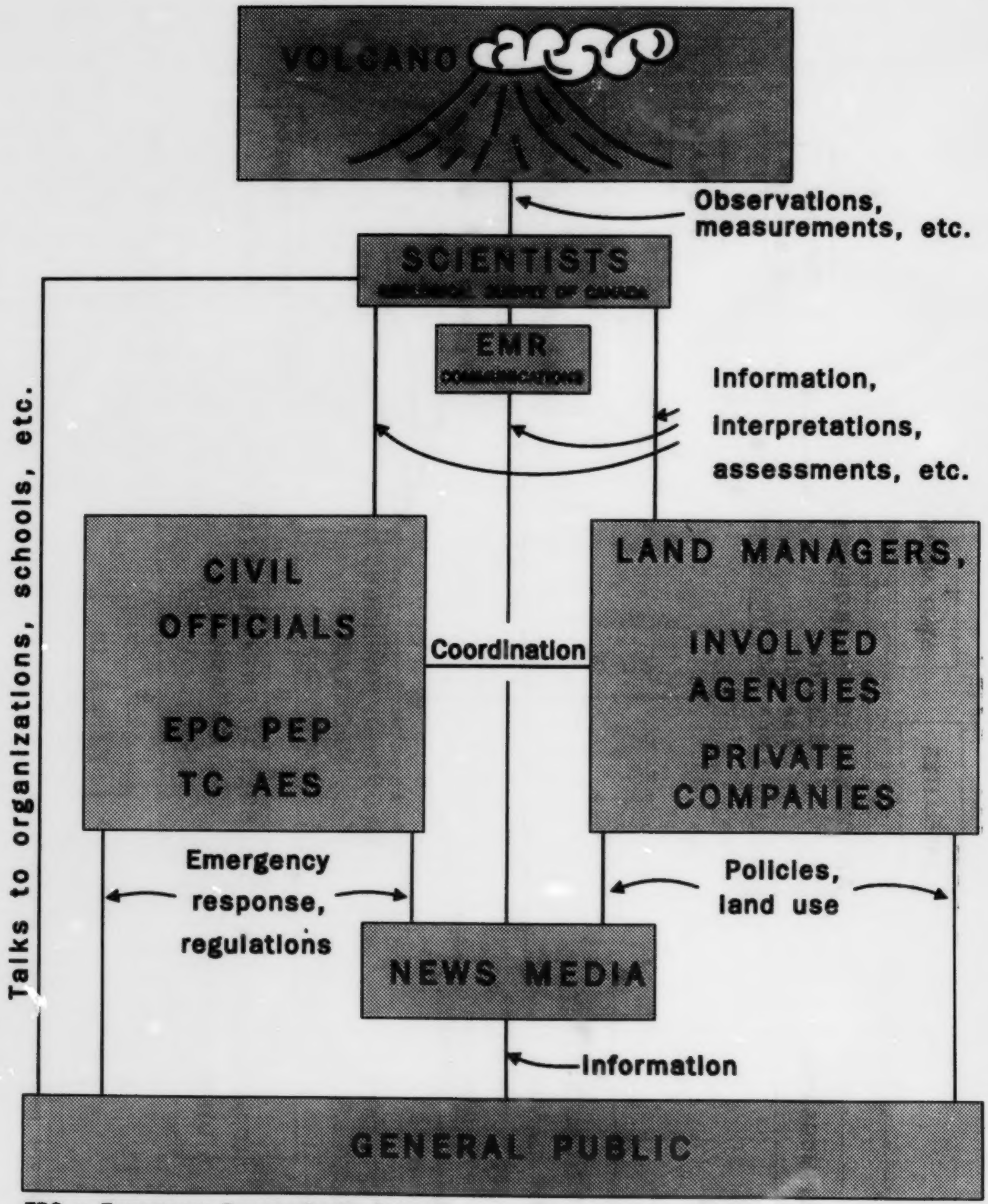
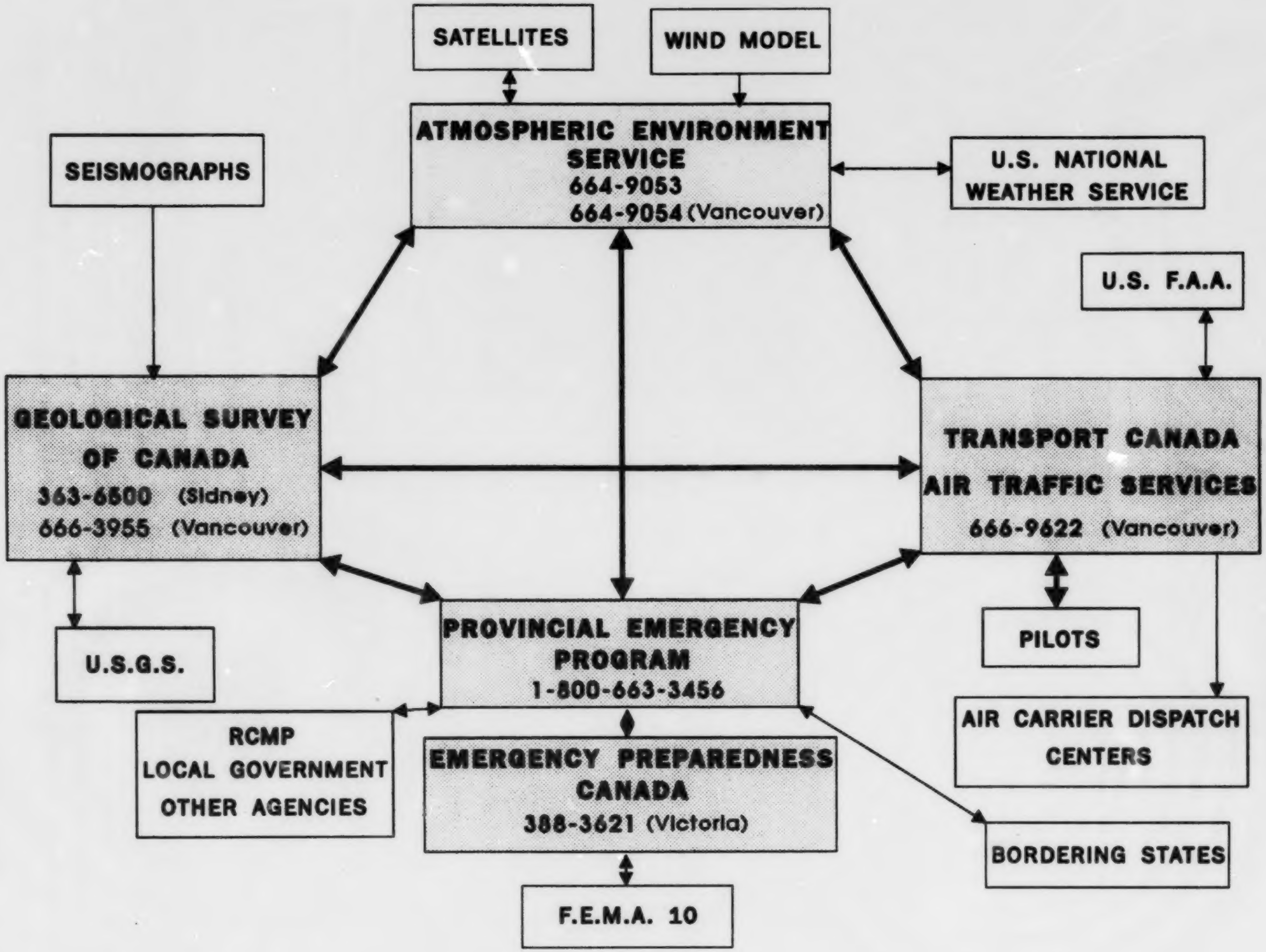

LEGEND
Rift zone
Subduction zone
Transform fault
Large felsic complex
Felsic complex, shield volcano or volcanic field (3 or more cinder cones)
Cinder cone; small shield volcano
Chilcotin Group basalt flows (Miocene-Pliocene)
Quaternary Chilcotin Group flows
Volcanic plug, feeder to Chilcotin basalts
Area of long lived volcanicity including Pleistocene eruptions
U.S.A.
CANADA
140
130
120
Yukon
River
Volcano Mtn.
DISTRICT OF MACKENZIE
Wrangell Volcanic Belt
Alligator Lake
Liard
River
YUKON TERRITORY
BRITISH COLUMBIA
Heart Peaks
Tuya Butte Volcanic Field
Level Mtn.
Stikine Volcanic Belt
Stikine River Volcanic Field
Stikine
River
Edziza Volcanic Field
Maitland Volcanics
Hoodoo Mt.
Iskut-Unuk River Cones
NORTH AMERICAN PLATE
The Thumb
Peace
River
QUEEN CHARLOTTE TRANSFORM
PACIFIC OCEAN
Tseax River Cone
Skeena
River
BRITISH COLUMBIA
ALBERTA
Athabasca River
QUEEN CHARLOTTE ISLANDS
Anahim Volcanic Belt
Nazko Cone
Rainbow Range
Itcha Mt.
Ilgachuz Range
Milbanke Sound Cones
Silverthrone
Franklin Glacier
Wells Gray-Clearwater Volcanic Field
Columbia River
EXPLORER PLATE
Alert Bay Volcanic Belt
Garibaldi Volcanic Belt
Bridge River Cones
Meager Mt.
Mt. Cayley
Fraser
PACIFIC PLATE
VANCOUVER ISLAND
JUAN DE FUCA PLATE
Mt. Garibaldi
CANADA
U.S.A.
0
200
Km

Figure 1: Quaternary volcanic vents in the Canadian Cordillera.


VOLCANO
Observations, measurements, etc.
SCIENTISTS
GEOLOGICAL SURVEY OF CANADA
EMR
COMMUNICATIONS
Information, interpretations, assessments, etc.
Talks to organizations, schools, etc.
CIVIL OFFICIALS
EPC PEP
TC AES
Coordination
LAND MANAGERS,
INVOLVED AGENCIES
PRIVATE COMPANIES
Emergency response, regulations
Policies, land use
NEWS MEDIA
Information
GENERAL PUBLIC

EPC = **Emergency Preparedness Canada**
PEP = **Provincial Emergency Program**
TC = **Transport Canada**
AES = **Atmospheric Environment Service**

Figure 2: Organizational plan for dissemination of information about volcanic eruptions (modified from Peterson, 1985).


SATELLITES
WIND MODEL
SEISMOGRAPHS
ATMOSPHERIC ENVIRONMENT SERVICE
664-9053
664-9054 (Vancouver)
U.S. NATIONAL WEATHER SERVICE
U.S. F.A.A.
GEOLOGICAL SURVEY OF CANADA
363-6500 (Sidney)
666-3955 (Vancouver)
TRANSPORT CANADA
AIR TRAFFIC SERVICES
666-9622 (Vancouver)
U.S.G.S.
PROVINCIAL EMERGENCY PROGRAM
1-800-663-3456
PILOTS
AIR CARRIER DISPATCH CENTERS
RCMP
LOCAL GOVERNMENT
OTHER AGENCIES
EMERGENCY PREPAREDNESS CANADA
388-3621 (Victoria)
BORDERING STATES
F.E.M.A. 10

All telephone numbers in bold are 24 hours

Figure 3: Communication pathways for notification, coordination and response of government agencies.

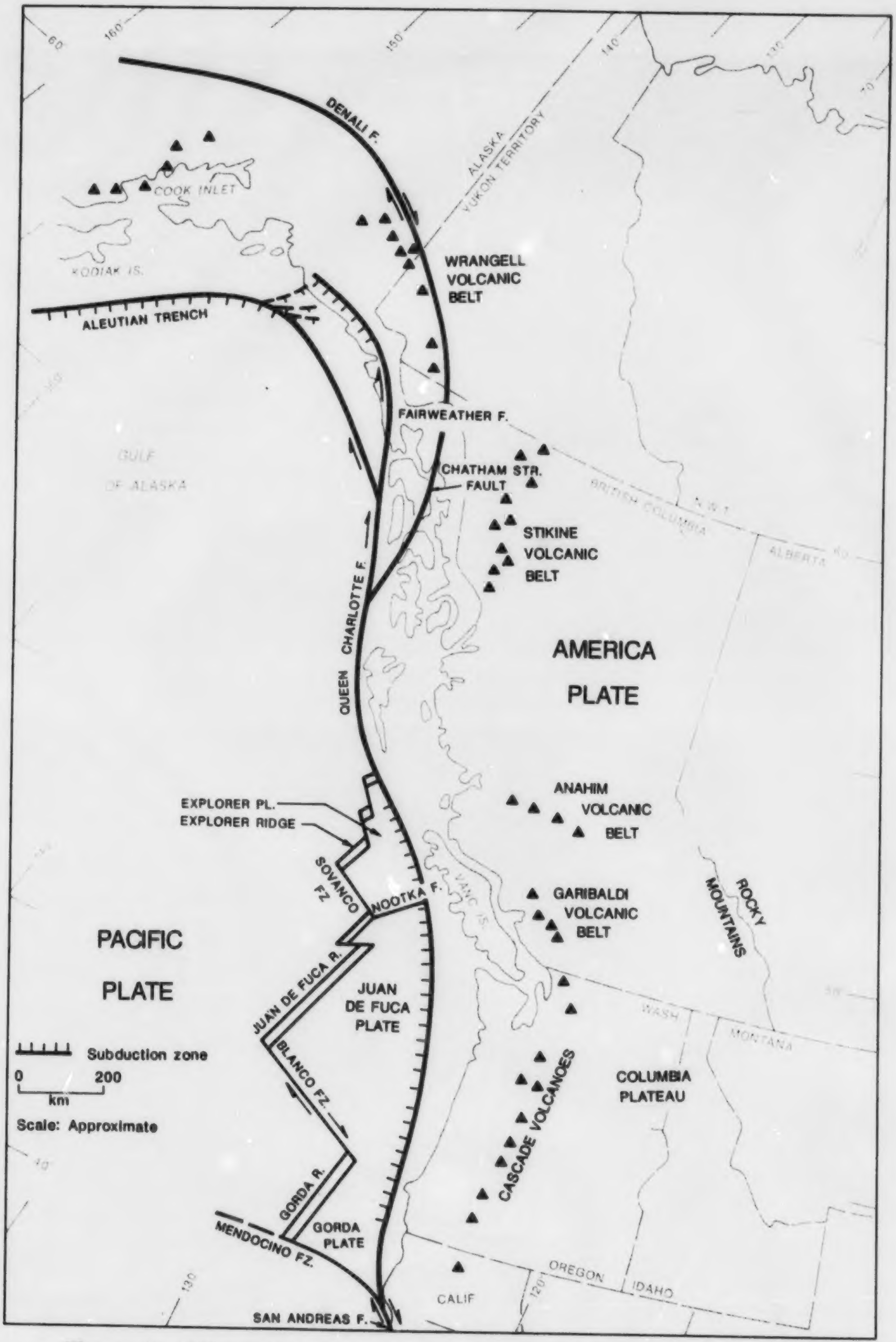

60
160
150
140
130
70
DENALI F.
ALASKA
YUKON TERRITORY
COOK INLET
KODIAK IS.
WRANGELL VOLCANIC BELT
ALEUTIAN TRENCH
GULF OF ALASKA
FAIRWEATHER F.
CHATHAM STR. FAULT
BRITISH COLUMBIA
N.W.T.
ALBERTA
60
STIKINE VOLCANIC BELT
QUEEN CHARLOTTE F.
AMERICA PLATE
ANAHIM VOLCANIC BELT
EXPLORER PL.
EXPLORER RIDGE
SOVANCO FZ
NOOTKA F.
VANC. IS.
GARIBALDI VOLCANIC BELT
ROCKY MOUNTAINS
PACIFIC PLATE
JUAN DE FUCA R.
JUAN DE FUCA PLATE
WASH
MONTANA
50
Subduction zone
0 200 km
Scale: Approximate
BLANCO FZ.
CASCADE VOLCANOES
COLUMBIA PLATEAU
40
GORDA R.
GORDA PLATE
MENDOCINO FZ.
OREGON
IDAHO
CALIF
120
130
SAN ANDREAS F.

Figure 4: Major tectonic structural elements and volcanic belts, California to Alaska.

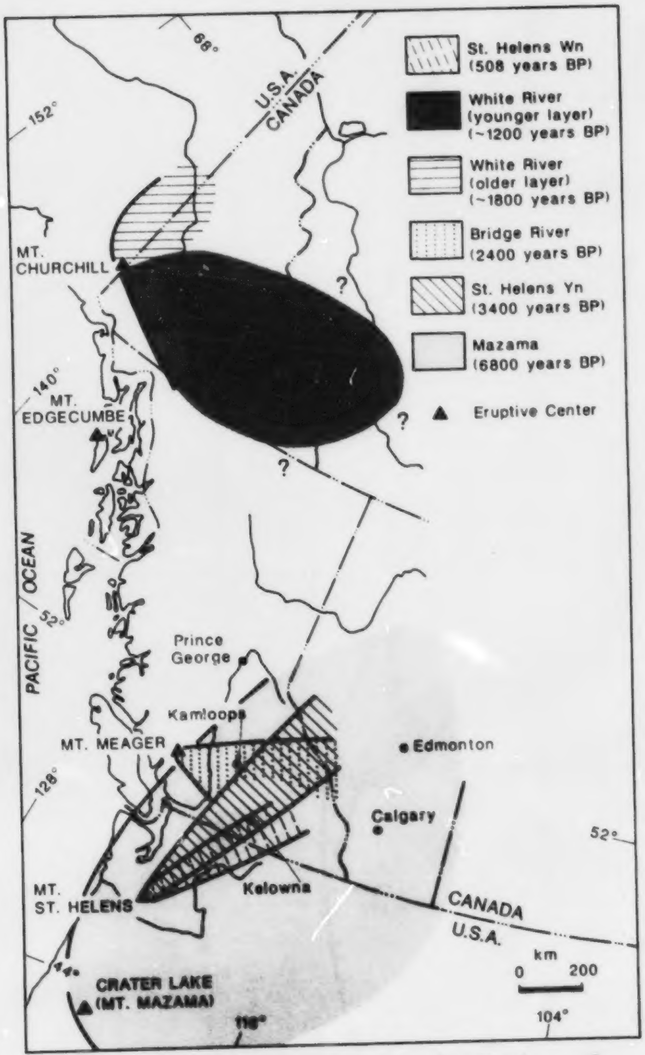

St. Helens Wn (508 years BP)
White River (younger layer) (~1200 years BP)
White River (older layer) (~1800 years BP)
Bridge River (2400 years BP)
St. Helens Yn (3400 years BP)
Mazama (6800 years BP)
▲ Eruptive Center
68°
152°
U.S.A.
CANADA
MT. CHURCHILL
?
140°
MT. EDGECUMBE
PACIFIC OCEAN
52°
Prince George
Kamloops
MT. MEAGER
Edmonton
128°
Calgary
52°
MT. ST. HELENS
Kelowna
CANADA
U.S.A.
km
0 200
44°
CRATER LAKE (MT. MAZAMA)
116°
104°

Figure 5: Presently known distribution of Holocene tephras in the Canadian Cordillera.

Figure 6: Mount Edziza volcano, 2700 metres high, in the Stikine Volcanic Belt, is part of a volcanic complex that began erupting about 8 million years ago and continued into the late Holocene.

Figure 7: Two metre thick tephra deposit, 1 km south east of Nazko cone, deposited during an eruptive phase 7200 years BP.

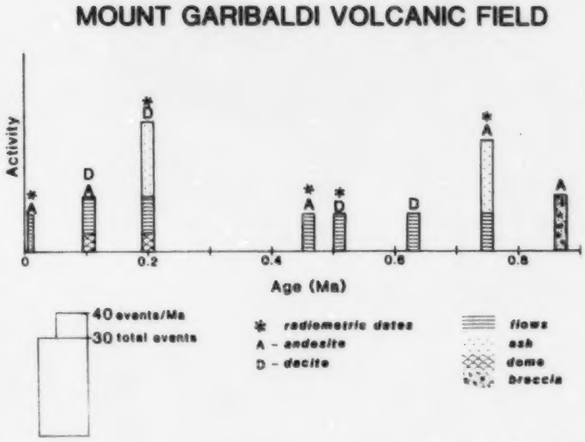


Figure 8: Diagrammatic representation of eruptive activity at the Mount Garibaldi Volcanic Field. Height of the histogram gives a very crude indication of the size of the eruption.

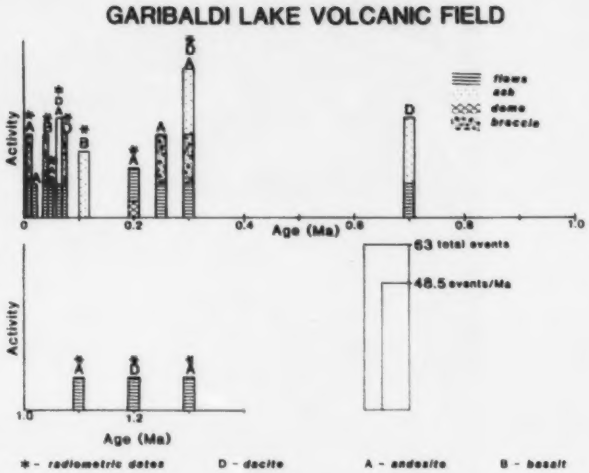


Figure 9: Diagrammatic representation of eruptive activity at Garibaldi Lakes Volcanic Field. Height of the histogram gives a very crude indication of the size of the eruption.

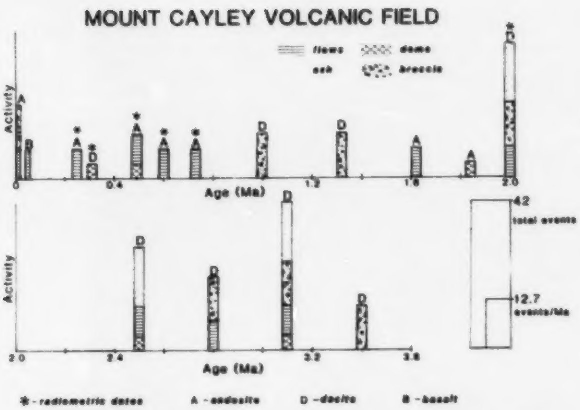


Figure 10: Diagrammatic representation of eruptive activity at Mount Cayley Volcanic Field. Height of the histogram gives a very crude indication of the size of the eruption.

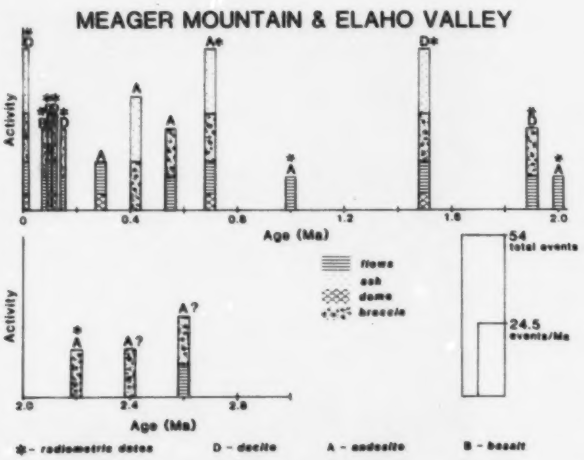


Figure 11: Diagrammatic representation of eruptive activity at Mount Meager Volcanic Complex. height of the histogram gives a very crude indication of the size of the eruption. The eruption 2300 years ago may have been on a scale similar to the May 18th, 1980 eruption of Mount St. Helens in Washington State.

Figure 11: Diagrammatic representation of eruptive activity at Mount Meager Volcanic Complex. height of the histogram gives a very crude indication of the size of the eruption. The eruption 2300 years ago may have been on a scale similar to the May 18th, 1980 eruption of Mount St. Helens in Washington State.

Figure 12: Vent area of the eruption from Mount Meager 2300 years ago. Crater is 1.5 kilometres wide at the rim.

QUANTIFICATION OF RISKS FROM SLOPE HAZARDS

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ABSTRACT

Landslides are rarely occurring events and standard statistical methods do not apply to their prediction. This paper discusses the derivation and use of subjectively selected probabilities of occurrence. The concept is not new to other disciplines but it is one which many earth scientists and geotechnical engineers are reticent to apply. Slope hazards can have high economic, environmental and social consequences. An example of decision making involving economic/environmental considerations using a subjective probabilistic approach is described and illustrated. Social consequences frequently involve threat to life, and planners and engineers employed by regulatory agencies are increasingly asked to advise on levels of acceptable risk. A multifaceted approach to this difficult and controversial issue is described, comprising: 1) quantification of risks to individuals and populations to permit meaningful comparison with other societal risks; 2) quantification of risks as a prerequisite to justifying funds or labour to maximize "life saved"; and, 3) consideration of public perceptions.

INTRODUCTION

With growing populations we increasingly face situations where communities and/or their infrastructure are threatened by landslides and similar slope hazards. As government and regulatory agencies search for answers on relative safety, and industry contemplates economic impacts of threatened facilities, they also become aware of the inadequacy of relying on qualitative statements of the likelihood of such hazards occurring. The consequence of these hazards is frequently high and although uncertainty can be tolerated, vagueness cannot.

Objective statistical procedures cannot be applied to rarely occurring landslide events; however, their potential occurrences can be quantified subjectively and expressed as probabilities. By doing so, we enlist the substantial benefits that accrue from probability theory. This paper discusses the application of probabilistic approaches to decision making involving both threat to life and economic considerations, which can also include quantifiable environmental concerns.

SELECTING AN ALIGNMENT... ECONOMIC CONSIDERATIONS

Figures 1 and 2 illustrate a commonplace condition in the mountains of Western Canada. A narrow valley is threatened by rock falls, debris torrents and, independently, snow avalanches. Yet another hazard stems from the river and its capability for severe floods and channel changes. A location engineer charged with selecting an alignment for a utility or transportation route is constantly challenged by such hazards. The normal procedure is to select two or more alternative alignments and to compare capital costs. Other "costs" inherent in risks to the works imposed by the hazards and risks to the environment brought about by attempts to avoid or mitigate the hazards, are left to the engineer's judgement. This judgement is frequently questioned by government regulators and special interest groups. Little wonder that the location engineer has encouraged recent attempts to quantify these risks and develop a rationale for their acceptance.

The purpose of the case history described below is to illustrate the application and importance of quantified risk assessment; it is based on fact but is in part hypothetical.

The situation portrayed in Figures 1 and 2 is in British Columbia. The valley contains an existing transmission (twin-lined) alignment, which provides power to an important industrial mill. In 1979, the rock fall area visible on the right side of the photograph (Figure 1) became active with a failure of 3.5 to 4 million cubic metres which ran out 700 metres from the apex onto the floodplain (Figure 2). In 1985 the area adjacent to it became active involving up to 1 million cubic metres of rock debris which ran out 300 metres. Still further downstream, in 1957, a debris torrent occurred which also reached the alignment. The bare apex of its fan is just visible in Figure 1.

The case centres on a decision to upgrade the existing transmission facilities. The three alternative alignments for a new line can be considered. Alignment A would follow the existing alignment, perhaps using the existing towers. Alignment B would follow the floodplain, with some towers in or close to the river. Alignment C would follow a hillside route well above the valley bottom.

The hazards to be considered, in addition to the rockfall/debris torrent threat to alignment A, are:

1) an avulsion of the river and other flood related events which could be exacerbated by the right of way clearing etc. for alignment B; and

2) a large snow avalanche area on the hillside route, alignment C.

The consequences of these hazards could be loss of power to the mill; and/or destruction of a productive fish habitat resulting in increased temporary losses to the salmon fishery. Since both assessment can be treated accordingly.

Risk can be expressed as the product of the probabilities of a series of events that lead to a financial loss, and where the causative hazards are mutually exclusive (as can be assumed for the above) the component risks are additive to produce a total risk. In simple terms, the transmission line route problem can be expressed as follows:

$$ARC = (P_T \times L_T) + (P_F \times L_F)$$

where:

ARC is the annual risk cost of all hazards (to society),

P_T is the annual probability of a complete loss of power supply,

L_T is the estimated dollar value of lost production etc. due to interruption of power (assumed $500,000 per day),

P_F is the change in annual probability of destruction of the fish habitat due to right of way clearing,

L_F is the estimated dollar value of temporary and/or any permanent effects on the fishery (assumed $750,000).

The procedure for computing the total ARC values for each alignment, is shown in Table 1. The values for P_T are governed by the requirement that both the existing and new transmission lines experience an outage at the same time so that a complete interruption of power results. They also depend on the allocated probabilities of the causative hazards given in Figure 2. The selection of subjective probabilities for rarely occurring natural events is discussed later in this paper.

P_T is an end result, the product of several events in a linkage which leads to a tower failure. The value of P_T (1:200) for alignment B has been selected on the assumption that although the recurrence of a 1:100 "large" rock slide would destroy one or more existing towers, there is only a 1:2 probability of a tower on the flood plain being destroyed.

It is also noteworthy that no allowance is made for failure of a tower on alignment B due to river erosion, even though these towers would typically be designed to withstand limited flood flows (*e.g.* 1:100) This is because the probability of failure of an existing tower is conditional on the period of an outage due to the washout of a tower on alignment B. Thus even if an outage on alignment B lasts for a month, the additional component of P_T from this exposure would be very low (*i.e.* 1:100 x 1:12 x 1:30 = 1:36 000). It is for this same reason that the P_T values for alignment C are so low. The foregoing assumes randomly occurring landslides. In practice, consideration is also given to the seasonal (non-random) occurrence of rockslides which usually tends to increase joint probabilities.

The P_F value allocated for alignment B is the increment above the existing background annual probability of damage to the fish habitat. For the purpose of this example it is assumed that 1:50 flood would destroy the habitat and that the effect of the clearing would be to increase its vulnerability such that a smaller 1:10 flood would have a similar effect. Thus the incremental effect

Table 1. Quantitative Risk Assessment of Alternative Routes (Annual Risk Costs).

Alignment	**Powerline Risks**			**Fishery Risks**			**Total Risks**
	P_T	L_T	ARC_T	P_F	L_F	ARC_F	ARC
		$\$10^6$	$\$10^3$		$\$10^6$	$\$10^3$	$\$10^3$
A. Slide area	1:30	7	233	-	-	-	233
	1:30	14	466	-	-	-	466
B. Floodplain	1:200	7	35	1:12.5	0.75	60	95
	1:200	14	70	1:12.5	0.75	60	130
C. Hillside	1:22,000	7	0.3	-	-	-	0.3
	1:11,000	14	1.3	-	-	-	1.3

Note: L_T values are based on a 2 and 4 week outage

Table 2. Quantitative Risk Assessment of Alternative Routes (Total Costs).

Alignment	**Total Risks**		**Cost of Construction**	**Total Cost**
	ARC	PV(80 yrs)		
	$\$10^3$	$\$10^6$	$\$10^6$	$\$10^6$
A. Slide area	233	1.75	5.0	6.75
	466	3.50	5.0	8.50
B. Flooplain	95	0.67	6.5	7.17
	130	1.0	6.5	7.50
C. Hillside	0.3	0.003	7.5	7.50
	1.3	0.013	7.5	7.51

of alignment B is given by a P_F value 1:10 - 1:50 = 1:12.5.

To complete the assessment, the present value (PV) of the annual risk costs spread over the life of the facility (80 years) at current interest rates (10 percent) is added to the capital cost of construction to produce total costs. Note that the present values shown in Table 1 allow for decreasing annual risk costs with time. This is appropriate to situations where the loss is so substantial that it would lead to major changes or abandonment as opposed to repeated replacement of the lost facility.

The procedure provides a basis for sensitivity analysis, debate and decision making. In the example used, note that the selection of alignment A through the slide area, although requiring the least outlay for construction, is very sensitive to the duration of the outage (because of its high probability). The optimal risk (lowest combined capital/risk cost) moves from A for a two week outage to B or C for a four week outage. Alignment B, the floodplain route, would be the most controversial and therefore may be abandoned in favour of A or C. Should alignment B be selected however, the procedure would provide a basis for agreement on funds for mitigation. It is also apparent that alignment C is a form of insurance against the slide hazard, requiring a premium to be paid up front in its higher construction cost. Some might consider this premium to be too high and would be tempted to gamble that an event would not occur during the initial years. No doubt they would seek further advise from the geologist.

PROJECTS INVOLVING RISK TO LIFE

Risk to life from such naturally occurring hazards as rock falls, debris flows and floods have been part of the history of the Canadian Cordillera and other mountainous areas throughout the world. Life is risky and there is a degree of risk that is acceptable depending on the circumstances. One approach is to quantify the risk to the life of an individual exposed to a hazard and make a comparison with other societal risks which he/she accepts or tolerates.

The annual probability of loss of life of an individual (PDI) exposed to a hazard can be computed as follows:

$$PDI = P_H \times P_{E:H} \times P_{L:E}$$

where:

P_H is the annual probability of the hazardous event,

$P_{E:H}$ is the probability of exposure of the individual given,

$P_{L:E}$ is the probability of loss of life given the exposure.

Consider the case of the proposed commuter highway through an area similar to that described in the previous section. If the highway is located along alignment A, approximately 1 kilometre of the facility would be exposed to a single rock slide hazard. Assuming a normal travelling speed of 80 km/h and use of the highway by a commuter twice per working day, the appropriate $P_{E:H}$ value is 1:1750. It is also evident that if a vehicle is hit by a slide, loss of life would result ($P_{L:E}=1$). With such a situation it is helpful to select an acceptable level of PDI and compute an allowable hazards probability.

Table 3 provides a selection of risks that North American society tolerates. It is apparent that an "acceptable" level depends on:

1) the individual and the occupation he/she is willing to pursue;

2) whether the risk is voluntarily assumed or one that is imposed (involuntary); and,

3) present values (which can change with time).

Society is willing to accept voluntary risks which are roughly 1000 times greater that involuntary risks. However, the individual member of society rarely has any control over the location of a highway and, given viable alternatives, he would have a right to expect that any imposed risks would not exceed those corresponding to the involuntary level.

For the above case, a PDI value in the range of 1:10 000 to 1:50 000 (the threshold of involuntary risks) equates to allowable P_H values of 1:6 to 1:29. Extra caution is also appropriate because additional risk can result from a vehicle stopping at a blockage caused by an initial failure, and the probabilities of 1:10 to 1:30 for alignment A (Figure 2) would provide a strong argument for discarding this alignment in favour of B or possibly C.

Projects involving a risk of multiple fatalities invoke a higher level of concern. Figure 3 shows the frequency of catastrophic events from selected hazards in developed areas of the northern hemisphere. A catastrophe is defined as the loss of ten or more lives during a single event. The landslide experience in Central Europe (Alps) is based on 750 years of historic records (Schuster and Fleming, 1986). The frequency of catastrophic landslide events in Japan based on 50 years of records is an order higher than that tolerated in Europe. This is not to say that the Japanese completely accept their situation, for the level of effort put into slide hazard investigation and disaster prevention is currently far higher in Japan than in Europe.

Canada's history is shorter and thus the number of recorded catastrophic events are few (Table 4). However it is evident that our experience more closely resembles that of Central Europe than Japan.

Data on catastrophic events compiled as in Figure 3 permits significant comparisons only when the sample size is known and taken into consideration. For example, the data indicates that annual probability of dam failures in the USA involving 100 or more fatalities is 1:17. However, individual modern earth-fill dams have reported annual failure rates ranging between 1:1500 and 1:25 000 (Tawil and Houston, 1986).

It is suggested here that the European experience given in Figure 3 constitutes an appropriate model of background experience for Canada.

Allowable probability levels for individual sites should be selected so that the cumulative effect of events at those sites would be compatible with the background model. Since there are abundant opportunities across Canada for large landslides to occur, probabilities two to three orders lower than those established by the country wide model are suggested as threshold values. Certainly society would expect the level of imposed risks on groups of people to be lower than in situations where only one or two people are exposed.

It must be kept in mind that one rapidly reaches the limitations of this approach. The Royal Society (1983) study group on risk assessment concluded that "very serious events are too rare .... to appear as a sequence - they are viewed (by society) as isolated disasters." However, many situations will fall into clear cut categories, obviously acceptable or unacceptable. It is the marginal situations that require rationalization.

Consider the case of a proposed recreational campground to be sited on the floodplain at the location described previously (Figures 1 and 2). In British Columbia the peak use of such areas extends from June through September and typically involves an average of 10 to 50 users. Assuming the slide hazard is a random event, this equates to an annual risk to the user group (PND) of 1:600. Even weighting the analysis to allow for non-random occurrence (both the 1979 and 1985 slides occurred in March) and a reduction in the size of the group during inclement weather when the risk of the hazard is greater, this result is clearly unacceptable. However if the proposed use was downgraded to a picnic or rest area, the equivalent PND value is reduced to the 1:10 000 - 1:20 000 range which falls within the threshold of acceptability using the above guideline. A wise planner would still search for alternatives with even less risk.

It is of interest to note that a typical PDI value for the campground user in the above case approaches 1:50 000 because of the limited exposure of the individual. Thus from the individual standpoint there would be little concern, and the PND values would govern the final decision.

Any decision making process concerning risk to life should involve several approaches. No paper on this topic would be complete without at least a brief coverage of qualitative approaches which are so often used to weight the results of quantitative procedures.

As mentioned above, most people would experience some difficulty relating to an event that had a return period of greater than 100 years, but this does not prevent them from having perceptions on acceptability. Irrespective of its source, virtually all of us are shocked by the occurrence of a catastrophe close to "home". However society's intolerance towards these events is registered not by the fact that we are shocked but

Table 3. Probability of Death of an Individual involved in Voluntary and Involuntary Activities.

VOLUNTARY INDIVIDUAL RISKS:	
National Leader (U.S. Pres.)	1:50
Rock Climbing	1:250(3)
Commercial Diving	1:350
Deep Sea Fishing	1:350
Offshore Oil and Gas	1:600
Air Travel (crew)	1:1000
Car Travel (B.C. 1984)	1:3500(2)
Motorcycle Racing	1:5000
Construction	1:1500 - 1:6000
Air Travel (passenger)	1:9000
Agriculture	1:9000
Skiing	1:10000(3)
Child Bearing (U.K.)	1:10000
INVOLUNTARY INDIVIDUAL RISKS (including low risk occupations)	
Manufacturing (building materials)	$1:15 \times 10^3$
Fire (U.K. average)	$1:50 \times 10^3$
Household Electrocution (Canada)	$1:65 \times 10^3$
Drowning (U.K. average)	$1:100 \times 10^3$
Manufacturing (clothing/footwear)	$1:200 \times 10^3$
Natural Hazards (Norway average)	$1:350 \times 10^3$
Lightning	$1:5000 \times 10^3$
Structural Failure	$1:10000 \times 10^3$

Notes:
1) Relative to the population employed in, or exposed to, the activity.
2) For an individual travelling 10000 kilometres/year.
3) Participation 100 hours/year.
Sources: Kinchin (1978); Rodin (1978); Cohen *et al.* (1978); Hestnes *et al.* (1980); Royal Society (1983); Ministry of Transportation and Highways (1984); Pack and Morgan (1988); B.C. Hydro (1989).

by the persistence of this shocked state and the period of inquiry. Several workers (*e.g.* Slovic, 1987) have identified, researched and ranked factors which affect these reactions. In the context of this paper, three of the most salient factors are familiarity, controllability (including ability to withdraw from the risk) and perceived benefits. Society views with a high degree of tolerance an airline crash with say 300 fatalities. This is because airline crashes occur with some regularity on an annual basis and are familiar, and also because the users derive a substantial benefit to their lifestyle. In other words although we would like to see aviation made safer, we are willing to accept present standards because we see no viable alternative. Society would be less tolerant towards the loss of a lesser number of lives due to a landslide destroying the campground described earlier. This is because there is a relative lack of familiarity with this type of event and also because the source is uncontrollable. The latter concern reaches a peak when permanent communities are found to be threatened by landslides because there is limited opportunity for residents to withdraw from the risk. Over the long term however, and providing no negligence has been shown, recreationists and residents alike would view such an event as one of several slides that occur from time to time which they must tolerate if they are to benefit from recreating or living in mountainous areas. Evans (1989) reports that 18 large slides have occurred in the Canadian Cordillera since 1855.

One final factor that should enter into any procedure is the efficient use of money or labour in reducing risk to life. Consider for example a utility company with many aging dams in its system, each with various deficiencies. Since the company has finite resources, it has an obligation to spend those funds allocated for upgrading the system efficiently, *i.e.* to spend the money where there is the greatest threat to life. In this context the term efficiency can be expressed as lives saved per dollar spent. Lind (1989) has suggested the use of a working lifetime as "the one common currency comparable for rich and poor people, in rich and poor countries....the lifetime efficiency compares the amount of life saved by a safety provision, prospect or program with the amount of life consumed in work on its implementation". This approach must not be confused with any attempt to place a value on life, which society finds unacceptable, but rather with maximizing the saving of life given limited resources for doing so. This is the reason society tolerates existing threats of catastrophic proportions which are well above the guideline discussed earlier. On the west coast of Canada older downtown areas consist predominantly of unreinforced brick buildings. The poor performance of these buildings under earthquakes with return periods measured in 100's of years would lead to substantial loss of life. However the cost, or at least the perceived cost of rectifying this situation would be so great that the efficiency of such an expenditure would be very low. In other words the money (or the labour associated with this money) could be spent more beneficially elsewhere either to save lives threatened from other sources or improve the quality of life.

Occasionally we find an anomalous outlay of funds to save lives exposed to a hazard. In 1980, the British Columbia Government commenced a buy-out programme of the village Garibaldi north of Vancouver. This programme was a response to an extensive study of a rock slide hazard and a previous court ruling which upheld an approving officer's refusal to permit further subdivision. An estimated 300 people (residents, recreationists and workers) were exposed to the hazard. By the time the buy-out programme was completed, approximately $17.4 million had been spent (Segard, 1985). The annual probability of a rock slide occurring has been estimated to average 1:1800. There is also a potential for independently occurring debris torrents with an estimated probability of 1:550, although these would have a less severe impact (Morgan, 1990). The efficiency of this expenditure equates to $6.21 million per life saved. It is of interest to note that cancer screening in the western world operates at an efficiency of roughly $30,000 per life saved (Lind, 1989).

Although the prime application of the efficiency approach is to existing situations, it is also a planning tool. Land use planners in Norway recognize the desirability of not exposing individuals to risks in the voluntary range (Table 2), but have proposed a "highest tolerable" annual risk level of 1:333 for dwelling houses in snow avalanche areas (Hestnes and Lied, 1980). They have found that five to ten houses are destroyed by avalanches for every fatality. Thus this proposed level equates to PDI values ranging between 1:1660 and 1:3330. They state that in certain parts of Norway it would be "impossible" to find suitable development areas which would satisfy the higher safety requirements suggested by Table 2. Presumably they mean by this that the cost of

Table 4. Landslide Catastrophes in Canada resulting in more that 10 Fatalities, 1889 - P.D. (100 yrs>)

YEAR	LOCATION	TYPE	FATALITIES
1889	Quebec City	Large rockslide	51
1903	Frank, Alta	Large rockslide	70
1915	Jane Camp (Brittania B.C.)	Rock waste failure(?)	56
1971	St.Jean - Vianney (Quebec)	Large clay slide	31

avoiding these areas, including the benefits forgone, would be prohibitive.

ALLOCATING PROBABILITIES TO RARELY OCCURRING EVENTS

How often have geologists, in expressing their opinions of the likelihood of a landslide described it as remote or likely, low or high probability, or (even worse) acceptable or unacceptable. After all, the highway engineer may find an annual probability of 1:500 acceptable whereas the community planner would find it completely unacceptable. Justifiably, we increasingly encounter refection of such terms or requests for clarification by quantifying them, if only broadly and relatively.

Most rarely occurring events lack sufficient data to permit standard statistical analysis leading to probable frequency or an annual probability of a future event. However the concept of probability can also be subjective, a "*degree of belief*" held by an individual or group of individuals about some uncertain event or quantity (Roberts, 1983; Einstein, 1988; Keeney and Winterfeldt, 1989). If this individual or group is the best available with respect to both professional capability and experience, then it is valid to apply those beliefs, expressed as probabilities, in decision making. This approach is sometimes criticized because its validity cannot be tested. In a scientific sense this is of course true, but socially the ultimate test that must be passed is in a public forum or courtroom. Furthermore such "criticism fails to recognize that risk estimation is a synthesis of science and engineering knowledge that has been brought about because it has a practical utility, and not as an attempt to establish a new branch of science" (Royal Society, 1983). In other words there is a job to be done and this approach satisfies our need for guidelines and an organized frame work within which to exercise our judgment. At the very least expressing a rare event as an annual probability allows for the possibility that it could happen tomorrow, which "remote" does not.

Where the economic consequence of a decision is high or it involves threat to life, the problem is usually best approached by obtaining a concensus of a group of specialists with pertinent experience in the hazardous event, rather than relying on a single individual however well informed he or she may be. Procedures for reaching this concensus have been discussed by Keeney and Winterfeldt (1989). It is important that there be opportunity for mutual discussion between specialists and that ample time be spent on those items that display greater sensitivity to the final decision. The process is a reiterative one. The end result will likely be a range of values which is an expression of the degree of uncertainty, and any subsequent analyses should reflect this.

Probabilities derived in this way should be referred to as "judged or allocated" to avoid any misunderstanding as to their origin. It follows that as new data, experience and/or understanding becomes available these allocated probabilities may change. One should be always conscious of the need for updating.

Confidence in the use of probabilities to express and process specialist opinions on the occurrences of hazards increases with:

1) understanding of the hazard mechanism, so that meaningful comparison can be made with experience elsewhere; and,

2) knowledge of any previous occurrences and magnitudes.

The latter information can be split into recent, historic and geologic. Detailed information on a recent event is particularly important because it can provide us with an opportunity to establish the return period of a particular event magnitude by studying causative events such as earthquake or hydrologic conditions. This information is also used to gauge historic occurrences as reported orally or through newspaper reports. Geological evidence usually consists of assessing the size of any previous events and dating them relatively (with respect to other deposits) or absolutely (*e.g.* C^{14} dating).

Where large first time events occur, we should search for evidence of recently changed conditions. The debris from a recent (June, 1990) debris avalanche which occurred near Kelowna, British Columbia resulting in three fatalities was found to rest directly on a glaciofluvial terrace. The hydrologic conditions leading up to the event were acute with an estimated return period in the 100's of years, but it is also evident that disturbance of the slope by forest harvesting was a significant factor (Golder Associates, 1991).

Where repetitive events at a given site occur, consideration must be given to probability of occurrence versus magnitude relationships. A change in the magnitude of a hazard results in a change in severity of the event. For example, events on debris torrent prone creeks vary from debris floods with minimal risk to life to rapidly moving debris flows (torrents) with substantial direct and indirect risk. Recent investigation of these problems have attempted to address this relationship by allocating probabilities to two or three levels of magnitude and the corresponding severity (Thurber Engineering, 1990). Figure 4 illustrates this concept; the curve is stylized and in reality may be stepped or irregular. The area under the curve represents the total risk of loss of life of an individual resident (PDI) from the hazard. Entire fans are risk zoned using this procedure. Severity can also change through a change in the area of impact of the hazard. Hsu (1975), Ui *et al.* (1986), Gardner (1980), Hungr and Evans (1989) and several others have reported observed relationships between the magnitude of rockslides/rockfalls and runout and fragment size. Much current work is under way. Resolution of the problem discussed in the first section of this paper (Figure 2) relies on an evaluation of the probability of the rockslide reaching the floodplain versus alignment A.

One of the limitations of the probabilistic approach to random events is that it does not allow for the economic value of time. Where the risks are concentrated, as is usually the case in natural hazard applications, there can be considerable vulnerability stemming from an early occurrence of the loss. In the transmission line routing problem discussed earlier, the decision maker's first inclination would be to select the alternative with the lowest initial cost and "invest" the savings to protect against a loss. Thus he really needs to know what the chances are of a rockslide occurring during the next 10 to 20 years rather than the 80 year life of the line. However should alignment A be selected and a slide occur within a year of completion, the total cost of such a decision would range between 12 and 19 million. Even with the largest of systems, there would be very limited opportunity to offset this loss with a "saving" elsewhere, as for instance is fundamental to the life insurance industry. With randomly occurring events the higher the annual probability, the higher this vulnerability.

However many natural hazards do not occur randomly. For example, the occurrence of a large debris torrent is dependent not only upon hydrologic events but also on the presence of sufficient debris in the channel of the creek. The available debris can be at a minimum following a large event and time is required for its replenishment. This aging concept may also apply to recurring landslide hazards as is illustrated in Figure 5. Even the occurrence of earthquakes is under review. The U.S. Bureau of Reclamation (1989) in a recent interim guideline on Dam Safety Modification Decision Making concluded that "the elapsed time since the last major event should be considered. Thus, earthquake occurrence is viewed as cyclic with changing probabilities of occurrence for large events at different times of the cycle". Obviously any evidence of aging of a hazard is an important consideration in the selection of probabilities, particularly if it allows us to weight them over the near term.

CONCLUDING REMARKS

Landslides and debris flows are usually rarely occurring events with insufficient background data to permit standard statistical analysis. When the social and/or economic consequences of a failure are high, it is important that a logical thought process be followed and the rationale for any decision documented. Thus it is not surprising that there is a growing demand for a probabilistic approach to decision making in this area. The approach requires geologists and geotechnical engineers to express their opinions quantitatively, as 'judged or allocated" probabilities.

In other disciplines, the use of probabilities to express expert opinions and beliefs has a lengthy history. The reasons for this are to provide clarity, avoid misinterpretation, focus on sensitive items and facilitate the processing of new information. This reasoning applies equally to the earth science and geotechnical fields.

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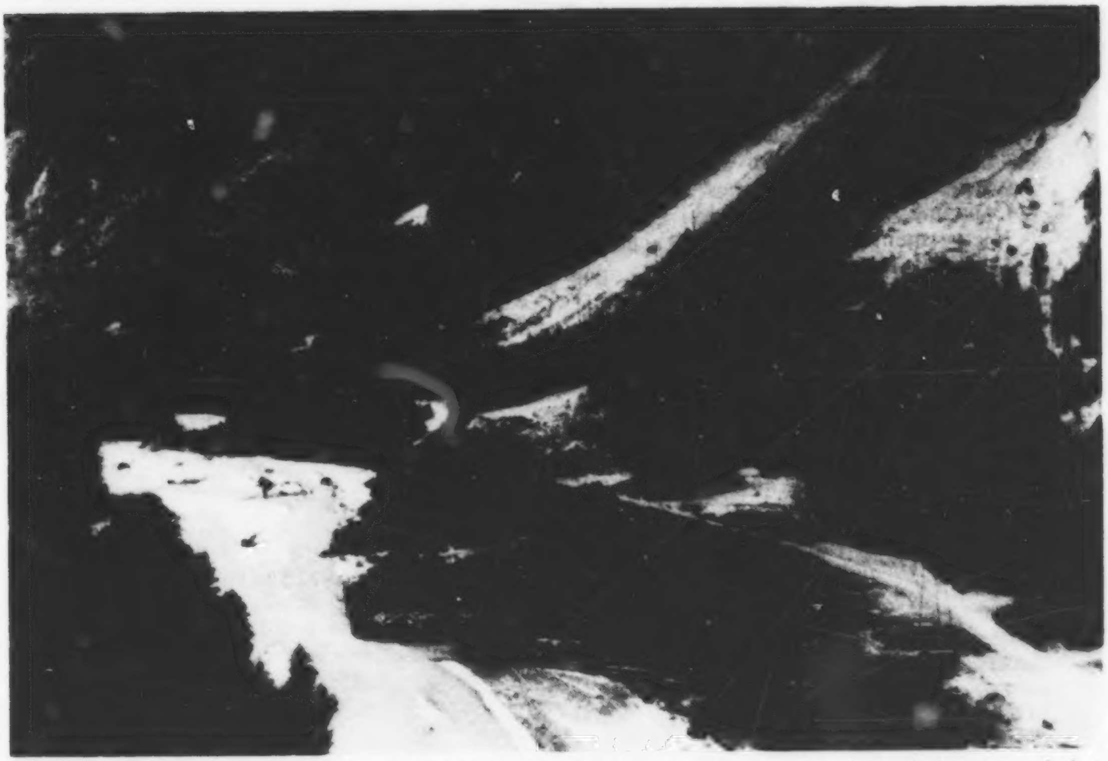

Figure 1: A mountain valley in British Columbia, looking downstream, showing existing transmission lines threatened by rockslides.

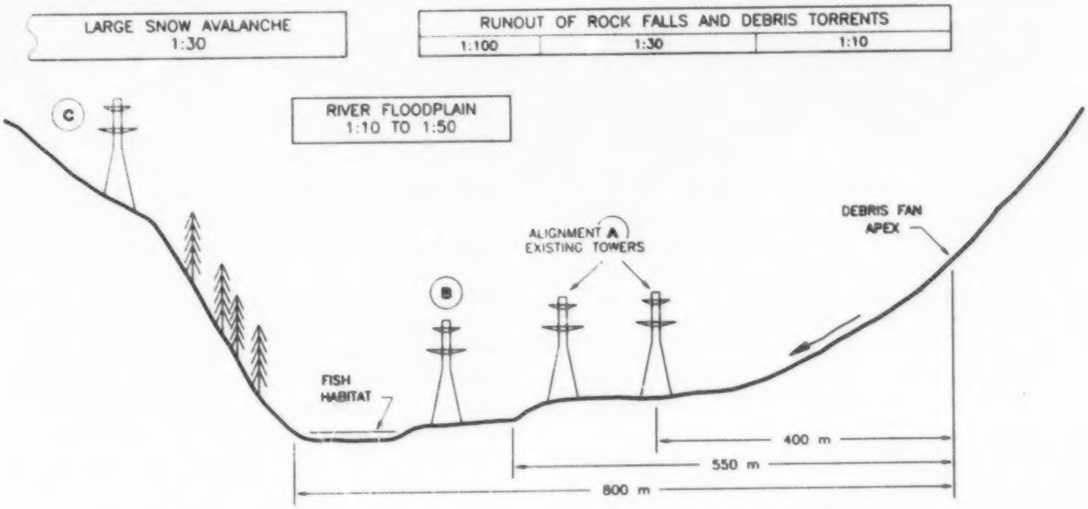
LARGE SNOW AVALANCHE
1:30
RUNOUT OF ROCK FALLS AND DEBRIS TORRENTS
1:100
1:30
1:10
C
RIVER FLOODPLAIN
1:10 TO 1:50
ALIGNMENT A
EXISTING TOWERS
DEBRIS FAN
APEX
B
FISH
HABITAT
400 m
550 m
800 m

Figure 2: Schematic section across valley at location of Figure 1.

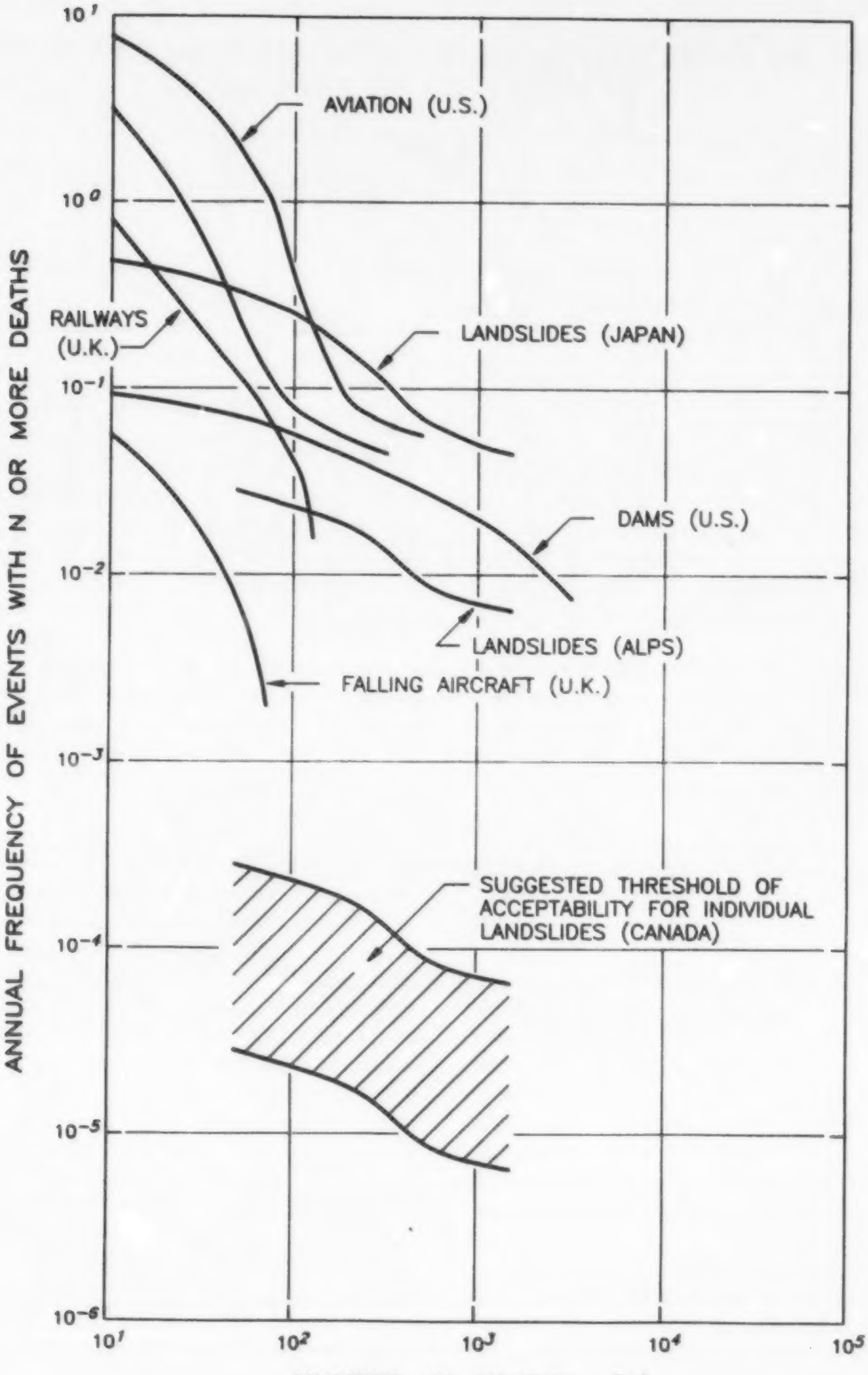

Figure 3: **Probability and frequency of multiple deaths from various natural and man-made sources based on reported occurrences (Kinchin, 1978; Royal Society, 1983; Schuster and Fleming, 1986).**

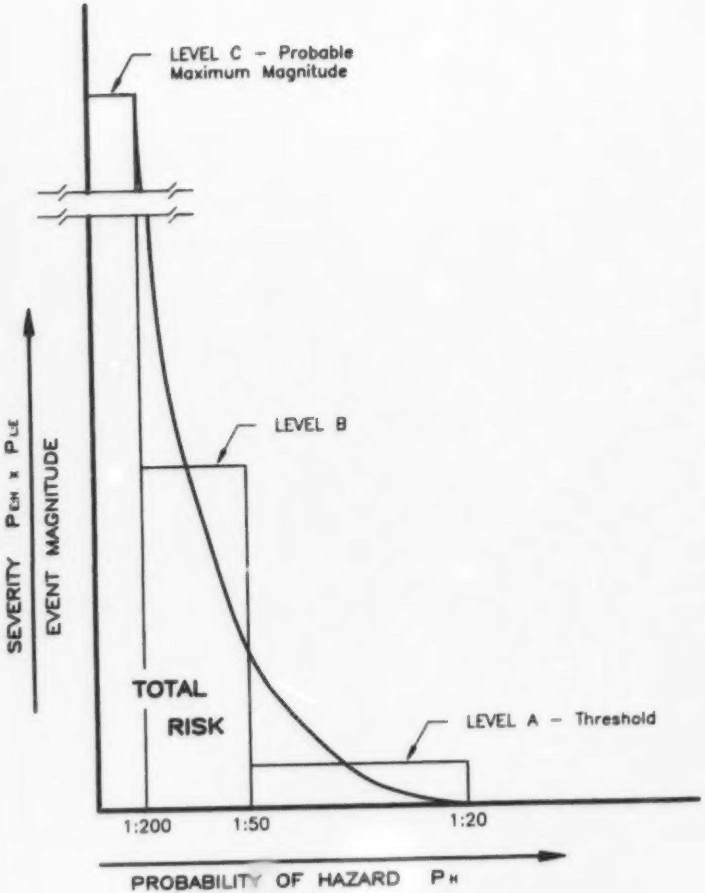

Figure 4: Total risk concept applicable to locations where magnitude and severity of event increases with decreasing probability of occurrence.

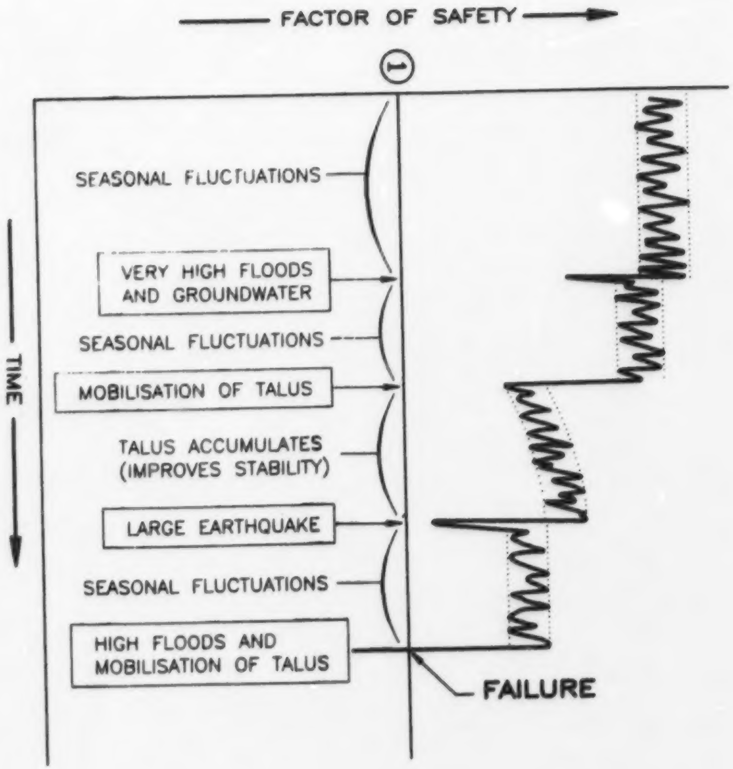

Figure 5: Schematic plot depicting potential for progressive aging prior to landslide.

HIGH MAGNITUDE-LOW FREQUENCY CATASTROPHIC LANDSLIDES IN BRITISH COLUMBIA

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ABSTRACT

High magnitude (volume > 1 million cubic metres) low frequency catastrophic landslides are a major hazard to economic development, public safety, and the environment in British Columbia. Twenty-six landslides of this type are known to have occurred in British Columbia since 1855. These events include rock avalanches from mountain slopes, debris avalanches from volcanoes and massive retrogressive spreading failures in Quaternary sediments adjacent to major river channels. The largest historical landslide is the 1965 Hope Slide (47 million cubic metres). Although most events have occurred in remote areas, 8 (32 per cent) of the events have impacted on the infrastructure of the province causing at least 80 deaths and many millions of dollars of damage. Rock avalanches can be highly mobile, rapid (reaching velocities up to 100 metres/second), and exhibit behavior difficult to predict. The detection of catastrophic potential in a deforming mountain slope remains a major problem in hazard assessment in the mountains of the province. The Quaternary volcanic rocks of the Garibaldi Volcanic Belt are particularly prone to large scale slope failures. Investigations of massive debris avalanche deposits at Mount Garibaldi, Mount Cayley, and Mount Meager have yielded evidence for the occurrence of massive debris avalanches during the last 5000 years in addition to several smaller events known to have occurred in historical time. For example, the Squamish River was blocked by a massive debris avalanche from Mount Cayley as recently as 500 years ago. Natural dams formed by landslides are a significant secondary hazard related to high magnitude landslide occurrence and have impacted on the fishery resource of the province. In 1888 a massive slide (15 million cubic metres) in Quaternary sediments occurred south of Ashcroft and blocked the Thompson River for 44 hours. In 1973 a landslide of comparable magnitude in similar materials blocked the Peace River near Fort St. John. Landslides may also generate destructive waves when they enter rivers or lakes.

INTRODUCTION

High magnitude-low frequency catastrophic landslides are a major hazard to public safety, the environment, and economic development in British Columbia. Recent studies have shown that strategic transportation corridors through the Cordillera have experienced high magnitude catastrophic landslides in the Holocene (Piteau, 1977; Evans, 1984b; Ryder *et al.*, 1990; Savigny, 1990; Naumann, 1990) and that significant rock avalanches have taken place in the vicinity of major resource development projects (*e.g.* Evans and Clague, 1990; Martin and Tod, 1990). Since the beginning of the historical period, taken to be 1855 for present purposes, such slides have been responsible for the deaths of over at least 80 people and hundreds of millions of dollars in direct and indirect damage to the infrastructure of the province.

Although less frequent than the smaller landslide events discussed by VanDine (this volume) a greater hazard is posed by the destructive potential associated with the occurrence of high magnitude events. These events include rock avalanches from mountain slopes, debris avalanches from volcanoes and massive retrogressive spreading failures in Quaternary sediments adjacent to major river channels.

This paper is a progress report of ongoing research by the writer at the Geological Survey of Canada. The paper also provides a framework for the assessment of hazards associated with high magnitude-low frequency landslides in British Columbia, with particular emphasis on the occurrence of large debris avalanches in the

Garibaldi Volcanic Belt located in the strategic southwest part of the province.

A high magnitude-low frequency catastrophic landslide is taken to be a large (volume generally in excess of 1 million cubic metres), rapidly occurring landslide in soil or rock. Included in this paper however are landslides which may have had a smaller volume than specified above but which were particularly destructive (*e.g.* the 1915 Jane Camp event) or which are examples of future, possibly larger, events in a similar environment (*e.g.* 1986 Mount Meager rock avalanche).

The physiographic subdivisions of British Columbia used in this report are those defined by Holland (1964).

REVIEW OF HISTORICAL RECORD

Historical data on the type and location of catastrophic landslides yields important information on the behaviour of susceptible geological environments and assists in identifying areas vulnerable to future landslide events.

Data assembled (Table 1; Figure 1) during the conduct of Geological Survey of Canada research into landslides in the Cordillera indicates that of 33 historical catastrophic landslides known to have occurred since 1855, 26 (79 per cent) have occurred in British Columbia. Sixteen events (61 per cent of B.C. total) have occurred in the Coast Mountains, 7 (26 per cent) occurred in the Garibaldi Volcanic Belt, 5 (19 per cent) occurred in the St. Elias Mountains, and 4 (15 per cent) occurred on Vancouver Island. Twenty-two (85 per cent) of the events involved rock slopes and 4 (15 per cent) occurred in Quaternary sediments. Thirteen of the 22 (59 per cent) rock avalanches recorded in B.C. occurred in rock slopes adjacent to glaciers. Eleven of the total B.C. events (33 per cent) occurred in Quaternary materials which include volcanic products, glaciolacustrine and glaciomarine sediments.

Twenty-five out of the 26 events (96 per cent) occurred in the western part of the province (Coast Mountains [including the adjacent Cascade Mountains and the eastern margin of the Thompson Plateau], the St. Elias Mountains and Vancouver Island). This area is, therefore, the most landslide sensitive region of the British Columbia. Although three major rock avalanches are known from the Alberta Rocky Mountains since 1855, no high magnitude events have been recorded from the B.C. Rocky Mountains during the same period.

Also of note is the occurrence of high magnitude-low frequency landslides involving Quaternary sediments adjacent to major rivers in the province.

Table 1 allows the identification of the most landslide susceptible regions of British Columbia viz. the Coast and St. Elias Mountains. Within the Coast Mountains, the Garibaldi Volcanic Belt, which occupies a strategic position in the southwest part of the province, is the most landslide-prone geological environment (Evans, 1984; 1990a; 1990b).

ROCK AVALANCHES

According to Table 1 rock avalanches are the most frequent historical high magnitude catastrophic landslide. As work continues on the evaluation of landslide hazard in the Cordillera it is becoming clear that rock avalanches are relatively common in certain geomorphic and geologic environments in British Columbia (*e.g.* Clague and Evans, 1987; Cruden, 1985; Cruden *et al.*, 1989; Eisbacher, 1979; Evans, 1984, 1988, 1989b, 1989c, 1990a; Evans and Clague, 1988, 1989, 1990; Evans and Gardner, 1989; Evans *et al.*, 1989; VanDine and Evans, in press). On Vancouver Island, for example, the region underlain by the Karmutsen Volcanics is particularly sensitive to rock avalanches (Figure 2) (Howes, 1981; Evans, 1989; VanDine and Evans, in press).

Within any area, regional geologic factors influence the distribution and behaviour of rock avalanches. In a regional study of rock slope failure in the Skeena Mountains, for example, Eisbacher (1971) documented the structural control on the distribution of 25 detachments and found that the direction of initial sliding was preferentially perpendicular to the structural trend.

A complex set of structural factors, detachment mechanisms, and triggers leads to the occurrence of a rock avalanche. Detachment is favoured on steep rock slopes where planar structural elements combine to form a detachment surface that may consist of a single surface or multiple surfaces. A planar detachment on one or more bedding planes resulted in the largest rock avalanche documented so far in British Columbia. The Valley of the Rocks rock avalanche (Figure 3), located in the Rocky Mountains 50 kilometres northeast of Radium Hot Springs, occurred in pre-historic times, on a west-dipping dip slope in Devonian Carbonates (Duffy, 1967; Leech, 1979). Debris covers an area of 12.6 square kilometres and has a volume in excess of 200 million cubic metres. In contrast the largest historical rock avalanche to have occurred in British Columbia, the 1965 Hope rock avalanche (Figure 4) [estimated volume 47 million cubic metres], occurred on multiple joint surfaces with variable dip as documented by Von Sacken (1991) and Von Sacken *et al.* (1992).

Detachment may result from simple translation as at The Valley of the Rocks and numerous other rock avalanches in British Columbia, or a combination of mechanisms. At the Mystery Creek rock avalanche [estimated volume 40 million cubic metres], 20 kilometres north of Whistler, for example, detachment on a low angle joint surface dipping toward the valley appears to have been preceded by toppling toward the valley involving flexural slip on foliation surfaces dipping away from the valley and into the slope (Figure 5). The characterization of the process by which slope deformation terminates in catastrophic detachment remains a current research problem in géotechnique.

Rock avalanches may occur without any detectable change taking place in the slope environment or be caused by a definable trigger such as an earthquake. A re-analysis of the 1965 Hope Slide by Weichert *et al.* (1990) suggests that the "earthquakes" associated with the landslide were probably generated by two phases of the landslide itself. This finding removes an obvious trigger for the Hope Slide. Analysis has shown that the pre-failure slope was in a stage of limiting equilibrium before the 1965 slide (Von Sacken, 1991) yet it had withstood substantial seismic accelerations in the past (Wetmiller and Evans, 1989). It is not clear how the slope that failed withstood such forces since according to slope stability analysis modest seismic forces should have been high enough to result in detachment. In contrast major earthquakes in B.C. have triggered rock avalanches. The M = 7.2 1946 Vancouver Island earthquake, for example, triggered several major landslides (Mathews, 1979) including the 1946 Mount Colonel Foster rock avalanche (Figure 6; Evans, 1989).

Post-detachment behaviour (mobility) varies according to such factors as the geometry of the rock avalanche path (Evans *et al.*, 1989), the volume of the detached mass (Evans *et al.*, 1989), and the characteristics of the surface over which the debris travels (Evans and Clague, 1988). An example of a highly mobile rock avalanche is the Pandemonium Creek event which occurred in 1959 (Figure 1). The debris travelled up to 9 kilometres from its source (Figure 7) and an analysis of the event indicated that the velocity of the debris may have reached 100 metres/second (Evans *et al.*, 1989).

It should also be noted that rock avalanches may produce secondary effects, including landslide dams and landslide-generated waves, which extend the zone of potential damage well beyond the limits of the debris (Evans, 1986).

The timing of pre-historic rock avalanches is being analyzed by C^{14} dating of organic fragments found above, within, or beneath landslide debris (*e.g.* Naumann, 1991). Unpublished dates obtained by the writer indicate that many pre-historic rock avalanches are younger than 5000 years. The largest body of radiocarbon dates has been assembled for rock/debris avalanches in the Garibaldi Volcanic Belt which will now be discussed in detail.

DEBRIS AVALANCHES IN QUATERNARY VOLCANIC ROCKS, GARIBALDI VOLCANIC BELT

The Garibaldi Volcanic Belt is the northward extension of the Cascade Volcanic Belt (Scott, 1990) (Figure 8). Quaternary volcanic rocks of the Garibaldi Group occur in three major centres, viz. Mt. Garibaldi, Mount Cayley, and Mount Meager.

The most recent eruption in the Belt was at Plinth Peak, within the Mount Meager Complex, at about 2350 years B.P. (Read 1983, 1990; Evans in press) which deposited the so-called Bridge River Ash (Nasmith *et al.*, 1967; Mathews and Westgate, 1980). Using the calibration curves of Stuiver and Becker (1986) the calendar date of the eruption is about 400 B.C.

The term "debris avalanche" is used here to describe the transformation of a volcano slope failure into what Schuster and Candell (1984: 567) define as "a sudden and very rapid flowage of an incoherent, unsorted mixture of rock and soil material...Movement of the mass is characterized by flowage regardless of whether it is wet or dry..." The term "debris avalanche" has been used in recent descriptions of catastrophic landslides in volcanic environments (*e.g.* Siebert, 1984; Francis and Wells, 1988).

DEBRIS AVALANCHES IN THE MOUNT GARIBALDI COMPLEX

Large landslides have taken place in two types of settings within the Garibaldi Complex; from the flanks of the volcanoes themselves (*e.g.* Mount Garibaldi) and from the high precipitous margins of lava flows at some distance from the source vent (*e.g.* Rubble Creek).

Major rock/debris avalanche deposits have been documented in the Mount Garibaldi-Cheekye River area and Rubble Creek.

MOUNT GARIBALDI-CHEEKYE RIVER

Debris avalanche deposits were first described in the Mount Garibaldi-Cheekye River area by Mathews (1952a; 1958). They cover a large area of the Squamish Valley and consist of large dacitic blocks set in a matrix of pulverized tuff/tuff breccia, typical of debris avalanche deposits described elsewhere (*e.g.* Crandell, 1971; Evans and Brooks, 1991).

Mathews has argued that Mount Garibaldi was partially built over Fraser Glaciation ice, the melting of which during deglaciation removed support from the volcanic edifice resulting in the collapse of its western flank. The process is summarized in Figure 9. According to this hypothesis the age of the debris would be about 10,000 years, since Mathews suggested that glacier ice was still present in the Squamish Valley at the time of the flank collapse.

The area of the debris [including the Cheekye Fan] is 25 square kilometres (Evans, 1990b). Assuming a mean thickness of 100 metres, this yields a volume of approximately 25,000 million cubic metres. Thus is identical to Mathews' (1952b) estimate and compares favourably to his estimate of the missing volume from the western flank of Mount Garibaldi (29,000 million cubic metres).

The debris avalanche deposits originated in the dacitic lavas and tuff-breccias which make up the western flank of Mount Garibaldi. The amphitheatre-shaped headwater region of the Cheekye River is in effect a massive landslide scar created by multiple failure events (Figure 10). Successive failure events may have built up what Mathews (1952a) termed the 'terraced fanglomerates' at the mouth of the Cheekye Valley. Based on unpublished radiocarbon dates obtained by the writer it is probable that large landslides continued to occur on the western slopes of Mount Garibaldi and travelled down the Cheekye Valley to the head of the Cheekye Fan at least into the first millennium A.D.

Debris flows of smaller magnitudes have occurred in the Cheekye River in pre-historic time. They followed the channel of the Cheekye River, below the Cheekye Fan surface and dammed or diverted the Cheakamus River. A radiocarbon date of 670 ± 50 years B.P. (GSC 4307) was obtained from beneath two debris flow units exposed on the north bank of the Cheekye River.

Debris flows have continued in historical times. As described by Jones (1958), following heavy rains in August 1958, a debris flow swept down the Cheekye River and formed a 5 metre high temporary dam across the Cheakamus River at its mouth. Local residents reported that a similar debris flow occurred in the 1930's (Jones, 1958).

RUBBLE CREEK

The Rubble Creek basin has been the site of at least two large rock avalanches and several debris flows during the Holocene (Mathews, 1952b; Moore and Mathews, 1978; Hardy *et al.*, 1978). The source of the landslides is 'The Barrier', a precipitous face forming the margin of a dacitic lava flow erupted from Clinker Peak (Figure 11; Mathews, 1952b). Much of the debris has accumulated in a large fan at the mouth of Rubble Creek. Subsurface investigations indicate that the volume of the fan is between 156 to 186 million cubic metres and contains between 5 to 10 separate landslide units averaging 5 to 10 metres in thickness (Hardy *et al.*, 1978). A weathered surface exposed near the mouth of Rubble Creek separates historic landslide debris from similar materials which are older than about 600 calendar years (Hardy *et al.*, 1978).

During the winter of 1855-56 a major part of The Barrier failed along vertical fractures producing a large rock avalanche (est. vol. 30 to 36 million cubic metres) [this volume estimate is from Hardy *et al.* (1978); earlier estimates ranged from 15 to 25 million cubic metres (Mathews, 1952b; Moore and Mathews, 1978)] that travelled 6 kilometres down Rubble Creek to the Cheakamus Valley on an average gradient of 7° (Figure 12; Moore and Mathews, 1978; Hardy *et al.*, 1978). Based on superelevation data the debris reached velocities in excess of 20 to 25 metres/second (Moore and Mathews, 1978). A more complex analysis of the movement in Hardy *et al.* (1978) suggested that velocities may have reached 60 metres/second in the upper part of the path and that the landslide decelerated down the valley emerging from it onto the fan at about 25 to 40 metres/second.

The main debris stream spread over the northern half of the Rubble Creek fan and blocked the Cheakamus River (Evans, 1986). Debris flows associated with and following the rock avalanche covered the southern sector of the fan (Hardy *et al.*, 1978). Debris floods initiated when the Cheakamus River overtopped the landslide dam, buried tracts of forest on the floor of the Cheakamus Valley up to 3.5 kilometres below Rubble Creek; numerous rooted stumps of trees killed by these floods are still visible in the banks of the river.

Between 1955 and 1957, B.C. Hydro constructed an earth and rockfill dam (Cheakamus Dam) across the Cheakamus River less than 1 kilometre north of Rubble Creek. The southeast abutment is located on the 1855-56 rock avalanche debris. Material obtained from a borrow pit in the 1855-56 debris (Figure 12) was incorporated into the core of the dam (Terzaghi, 1960a, 1960b).

A ban on the development of a housing subdivision on the fan was upheld by the B.C. Supreme Court in 1973 (Berger, 1973) because of the risk of another catastrophic landslide from the steep margins of the Rubble Creek lava flow. In 1981 a Provincial Order in Council under the Emergency Program Act designated the Rubble Creek area too hazardous for human habitation. Property owners in the area were bought out, or relocated, at a cost of $17 million.

DEBRIS AVALANCHES FROM MOUNT CAYLEY

Investigation of diamicton units exposed in an extensive accumulation of volcanic debris in the Squamish Valley, west of Mount Cayley volcano (Figure 13), has yielded evidence for the occurrence of at least three major debris avalanches, initiated by the collapse of its western flank in the mid-Holocene (Evans and Brooks, 1991).

Radiocarbon dates obtained from tree fragments contained in the deposits indicate that the events took place in 4800, 1110, and 500 years B.P. All three events dammed the Squamish River and formed temporary lakes upstream of the debris (Brooks and Hickin, 1991).

As described by Evans and Brooks (1991), failure of the cone took place after considerable dissection of the original edifice had exposed weak pyroclastic materials at the base of the steep upper slope of the volcano. No evidence of older debris avalanches from Mount Cayley has been discovered.

Smaller scale debris avalanches involving mechanically weak pyroclastic materials continue to occur from Mount Cayley's western flank in historic time. A 1963 event (est. vol. 5 million cubic metres) has been described by Souther (1980) and Clague and Souther (1982). The fahrböschung of the landslide was 22° and velocities, calculated from superelevation data, reached 15 to 20 metres/second.

In 1984 a similar debris avalanche took place (Figure 14) but its volume was an order of magnitude smaller (est. vol. 0.5 million cubic metres). The event showed hyper-mobile characteristics, *i.e.*, the debris distance of travel was typical of a debris avalanche an order of magnitude greater. The fahrböschung for the 1984 landslide was 19° and based on superelevation measurements, velocities reached at least 31 metres/second. The 1984 event initiated debris flows in the lower reaches of Turbid Creek which entered the Squamish River and temporarily dammed it (Evans, 1986; Jordan, 1987; Cruden and Lu, 1989).

Debris avalanches from Mount Cayley and the effects of a possible damming of the Squamish River are major geomorphic hazards to public safety and economic development in the Squamish Valley.

ROCK/DEBRIS AVALANCHES IN THE MOUNT MEAGER COMPLEX

Most if not all slopes within the Mount Meager Complex show evidence of slope movement. A wide range of landslide types exists within the complex (Jordan, 1987).

LANDSLIDES INTO THE LILLOOET VALLEY

Volcanic debris covers most of the Lillooet Valley floor from the vicinity of Meager Creek to Mosaic Creek a distance of 17 kilometres. Some of this material was emplaced during the Plinth Peak eruption (the Bridge River assemblage) about 2350 years B.P. as pyroclastic flows as discussed by Read (1977, 1990) and Stasiuk and Russell (1989, 1990) but other units within the assemblage are undoubtedly landslide deposits (Figure 15; Evans, in press) and at least two major rock avalanche units associated with the Plinth Peak eruption have been distinguished (Evans, in press).

Evans (1987) has described the 1986 rock avalanche from the north side of the peak of Mount Meager (Figure 16). The detached mass of Pleistocene rhyodacite had an estimated volume of 0.5 million cubic metres.

LANDSLIDES INTO MEAGER CREEK

Large rock avalanches have occurred in Capricorn Creek and in Angel Creek on the south side of the volcanic complex. The rock avalanche in Capricorn Creek was investigated by Croft (1983). It occurred during the 1920's in fractured, altered quartz diorite basement rock. The landslide had a volume of > 1 million cubic metres and travelled 3 kilometres. The landslide debris is a major source area for the Capricorn Creek debris flows (Jordan, 1987).

A massive rock avalanche of unknown age originated in andesitic flows on the south face of Pylon Peak and descended Angel Creek spreading out in the Meager Creek valley. The extent of the debris was mapped by Jordan (1987) and covers an area of 5 square kilometres. Assuming an average thickness of 20 metres the volume is in the order of 100 million cubic metres.

LANDSLIDES INTO DEVASTATION CREEK

Exposures of a pre-historic debris avalanche deposit are found on Devastation Creek near its confluence with Meager Creek on the west side of the volcanic complex. Wood collected by P. Jordan from upright dead trees (Figure 17) in these deposits gave a radiocarbon date of 2170 ± 60 years B.P. (GSC 4302).

In historical times the effect of a major landslide at Devastation Glacier was reported by Carter (1932). Carter and his fellow climbers noted the deposits of a large rock/debris avalanche from the flanks of The Devastator which had travelled over Devastation Glacier, down Devastation Creek and into Meager Creek itself. The landslide was believed to have occurred in October 1931 since a large flood [probably due to a breaching of a landslide dam] in Meager Creek had been noted at that time by a local trapper.

A likely source area for the 1931 event is on the western flank of The Devastator adjacent to the 1975 slide and involving similar rocks. The 1931 event was larger than the 1975 event as is evident in the trimlines in the vegetation in 1947 aerial photographs which extend beyond the Neoglacial limit on Devastation Creek and down into Meager Creek.

Also evident in the 1947 aerial photographs is fresh landslide debris on the surface of Devastation Glacier which had its source on the west side of the valley directly opposite the 1975 rockslide site. The landslide involved Pleistocene andesitic flows and pyroclastics. The landslide is assumed to have taken place in 1947 because the debris does not show any distortion due to glacier movement. The volume of the 1947 landslide is estimated to be in the order of 2 to 4 million cubic metres. The landslide travelled a distance of about 1500 metres on Devastation Glacier but did not extend beyond its toe.

On July 22, 1975 a complex series of landslide events took place at Devastation Glacier when approximately 13 million cubic metres of altered Quaternary pyroclastic materials and glacier ice was lost from the west flank of Pylon Peak (Figure 18; Smith and Patton, 1984). The events were initiated by a rockslide which continued down Devastation Creek valley as a high velocity debris avalanche. The debris ricocheted back and forth between the valley walls rising up to 100 metres above the valley floor at the outside of bends in the valley before coming to rest at Meager Creek. Peak velocity estimates are 36 metres/second. Four men were killed by the landslide.

The overall length of the slide path was 7 kilometres and the vertical height of the path was 1220 metres yielding a fahrböschung of 10°. The debris avalanche was followed by major debris flow formed from the talus deposits of ice and soft rock which had collected in a portion of the debris avalanche scar. Both slides travelled roughly the same distance. The debris avalanche also triggered a major secondary slide on the western flank of the Devastator.

LANDSLIDES IN QUATERNARY SEDIMENTS

At least four major catastrophic landslides have taken place in Quaternary sediments (Table 1, Figure 1) on natural slopes adjacent to major rivers in British Columbia in the historical period. Materials involved in these events consist of Pleistocene glaciomarine and glaciolacustrine sediments, the geological and geotechnical properties of which have been reviewed by Evans (1982).

HANEY

On January 30, 1880 a major landslide (estimated volume 1 million cubic metres) occurred at Haney in the glaciomarine sediments on the eroding north bank of the Fraser River. Eyewitnesses reported that they heard the cracking of the ground and watched as a "great...moving mass of earth and trees...slid into the Fraser River." (Victoria Daily Colonist, February 5, 1880). The slide partially blocked the Fraser River and resulted in the death of 1 person [killed by the 12 metres high displacement wave caused by the slide] and substantial property damage to docking facilities along the Fraser. Excess pore pressures in sandy interbeds in the sensitive glaciomarine silts and clays and erosion at the toe of the slope by the Fraser River are probable causes of the slide (Evans, 1982). Trees were still erect on the displaced mass when it came to rest in Fraser River, suggesting a spreading type of failure.

ASHCROFT

A second major landslide (Figure 19) occurred in the 1880's when the Thompson River, near Ashcroft, was dammed by a landslide (estimated volume 15 million cubic metres) at approximately 2100 h on October 14, 1880 (Stanton, 1898; Evans, 1984a). The landslide occurred in Pleistocene varved glaciolacustrine silt. A lake quickly formed upstream of the landslide dam (Evans, 1984a) and attained a maximum depth of between 18 and 25 metres [the maximum pool elevation of the reservoir was approximately 306 metres above sea level]. At the mouth of the Bonaparte River, the rising water flooded Harper's Mill. The lake began to empty through a channel cut by workmen across the top of the dam at approximately 1700 h on October 16, 1880, after a life of approximately 44 hours. Catastrophic breaching of the dam did not take place since the escaping waters gradually enlarged the spillway until the lake was empty.

Irrigation was thought to be a cause of the landslide (Stanton, 1898). Other landslides which disrupted the Canadian Pacific Railway track along the Thompson River were also thought to be caused by irrigation. The C.P.R. has sought compensation through litigation (Cambie, 1902; Mr. Justice Wallace, 1987).

SPENCES BRIDGE

A large landslide occurred just south of Spences Bridge on the west side of the Thompson River valley at 1530 h on August 13, 1905. A large mass consisting mainly of Pleistocene glaciolacustrine silt suddenly broke away from the valley wall and descended at great velocity to Thompson River. There the slide debris generated a wave 3 to 5 metres high that swept across and up the river, destroying everything in its path, including an Anglican church at a Native Indian village. The tremendous force of this wave is illustrated by the fact that a horse tied to a hitching post on the valley floor had its tie rope broken and was carried upstream almost 300 metres before being thrown ashore. The slide material dammed Thompson River for about 5 hours, thus impounding a lake up to 13 metres deep. This lake drained rapidly when the landslide dam was over-topped. Fifteen people were killed as a result of the landslide, 5 buried in the debris and 10 drowned by the displacement wave.

The antecedent conditions are not clearly known. However, unpublished notes by H.J. Cambie, consulting engineer to the Canadian Pacific Railway, indicate that previous landslides had occurred at the site in 1880 and 1899. These slides and the 1905 slide were thought by Cambie to be caused by irrigation on the bench behind the landslide.

ATTACHIE

On May 26, 1973, in the Alberta Plateau of northeast British Columbia, the Peace River was blocked by a major retrogressive landslide in the vicinity of Attachie, 49 kilometres west of Fort St. John (Figure 20). The catastrophic failure took place near the base of Pleistocene glaciolacustrine sediments. The area of the landslide is 400,000 square metres and its mean depth is about 60 metres yielding a volume of about 24 million cubic metres.

This volume estimate indicates that it is one of the largest historical landslides to have occurred in Canada since 1855 and the second largest landslide in British Columbia to have occurred in the same period.

The landslide has not been documented in the literature but is of considerable interest since no human activity is present and the failure surface is located well above the river surface indicating that toe erosion was not a factor.

CONCLUSIONS

Although most of these events have occurred in remote areas, 8 (32 per cent) of the events have impacted on the infrastructure of the province and caused at least 80 deaths and hundreds of millions of dollars of damage. This translates into an annual probability of 5.8 per cent for a high magnitude landslide impact on the infrastructure of the province for the period of record 1855-1991.

High manitude low frequency rock avalanches can impact on structures located a substantial distance from their source slopes and can reach velocities up to 100 metres/second. Quaternary volcanic rocks of the Garibaldi Volcanic Belt are particularly susceptible to both pre-historic and historic high magnitude landslides. Important landslides have also taken place in unconsolidated Quaternary sediments.

High magnitude landslides may also produce important secondary effects including landslide dams (Evans, 1986), which have had a major impact on the salmon fishery of the Province (Evans, 1986; Ryder *et al.*, 1990), and landslide-generated waves (Evans, 1989). Both these effects extend the zone of potential damage well beyond and limits of the debris.

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Table 1. Known historical high magnitude catastrophic landslides in British Columbia.

LOCATION	REGION	EVENT	YEAR	DEATHS
ROCK AVALANCHES				
1	CM(GV)	Rubble Creek	1855-56	
2 •	CM(GV)	Mount Meager	1986	
3 •	CM(GV)	Devastation Creek 1	1931	
4 •	CM(GV)	Devastation Creek 2	1947	
5 •†∞	CM(GV)	Devastation Creek 3	1975	
6	CM(GV)	Mount Cayley 1	1963	
7	CM(GV)	Mount Cayley 2	1984	
8 †∞	CA	Hope	1965	4
9 •	CM	Tim Williams Glacier	1956	
10 •	CM	Pandemonium Creek	1959	
11 •	CM	Capricorn Creek	1920s	
12 •	CM	North Creek	1986	
13 †∞	CM	Jane Camp	1915	56
14 •	SE	Black Glacier 1	1990	
15 •	SE	Black Glacier 2	1991	
16 •	SE	Towagh Glacier	since 1950	
17 •	SE	Tweedsmuir Glacier	since 1972	
18 •	SE	Jarvis Glacier	since 1950	
19 ∞	VI	Mount Colonel Foster	1946	
20	VI	Kennedy River	1970	
21	VI	Kaouk River	1925-26	
22	VI	Conuma River	1974	
LARGE LANDSLIDES IN QUATERNARY SEDIMENTS				
23 †∞	CM	Haney	1880	1
24 ∞	TP	Ashcroft	1888	
25 †∞	CM	Spences Bridge	1905	15
26 ∞	AP	Attachie	1973	

Location number refers to Figure 1. Regions: CM = Coast Mountains (GV = Garibaldi Volcanic Belt); CA = Cascade Mountains; SE = St. Elias Mountains; VI = Vancouver Island; TP = Thompson Plateau; AP = Alberta Plateau. • = landslides adjacent to glaciers. † = deaths. ∞ = impact on economic infrastructure.

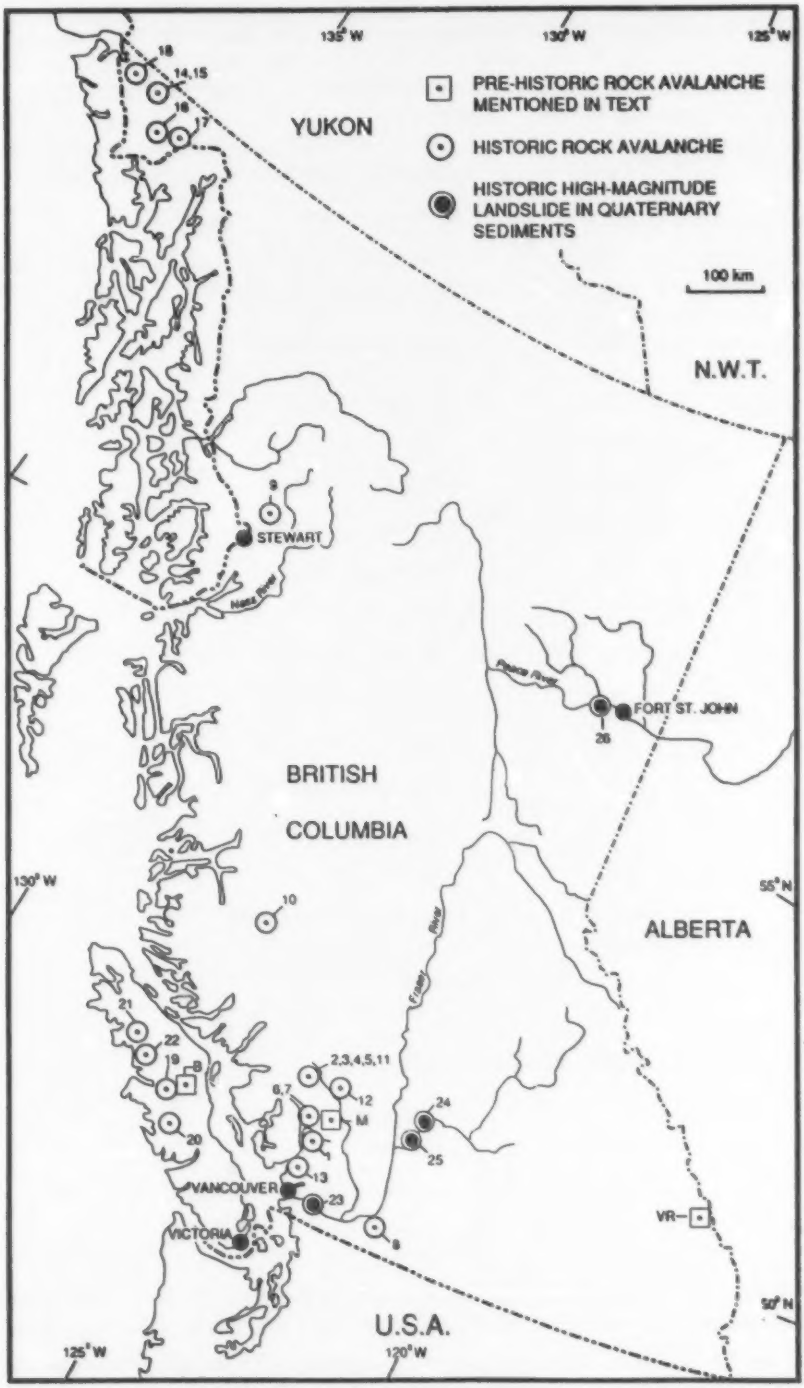

135° W
130° W
125° W
PRE-HISTORIC ROCK AVALANCHE MENTIONED IN TEXT
HISTORIC ROCK AVALANCHE
HISTORIC HIGH-MAGNITUDE LANDSLIDE IN QUATERNARY SEDIMENTS
100 km
YUKON
N.W.T.
18
14,15
16
17
9
STEWART
Nass River
Peace River
FORT ST. JOHN
26
BRITISH COLUMBIA
130° W
55° N
10
ALBERTA
Fraser River
21
22
19
B
20
2,3,4,5,11
12
6,7
M
1
13
24
25
VANCOUVER
23
VICTORIA
8
VR
50° N
U.S.A.
125° W
120° W

Figure 1: Map showing location of high magnitude low frequency catastrophic landslides in British Columbia discussed in tesxt. Numbers refer to known historic high magnitude landslides in Table 1. Letters refer to prehistoric high magnitude landslides discussed in text as follows: B = Buttle Lake rock avalanche, M = Mystery Creek rock avalanche, V = Valley of the Rocks rock avalanche.

Figure 2: Oblique aerial view of the prehistoric Buttle Lake rock avalanche, Vancouver Island (see Fig. 1 for location). The rock avalanche is one of several on Vancouver Island involving volcanic rocks of the Karmutsen Formation.

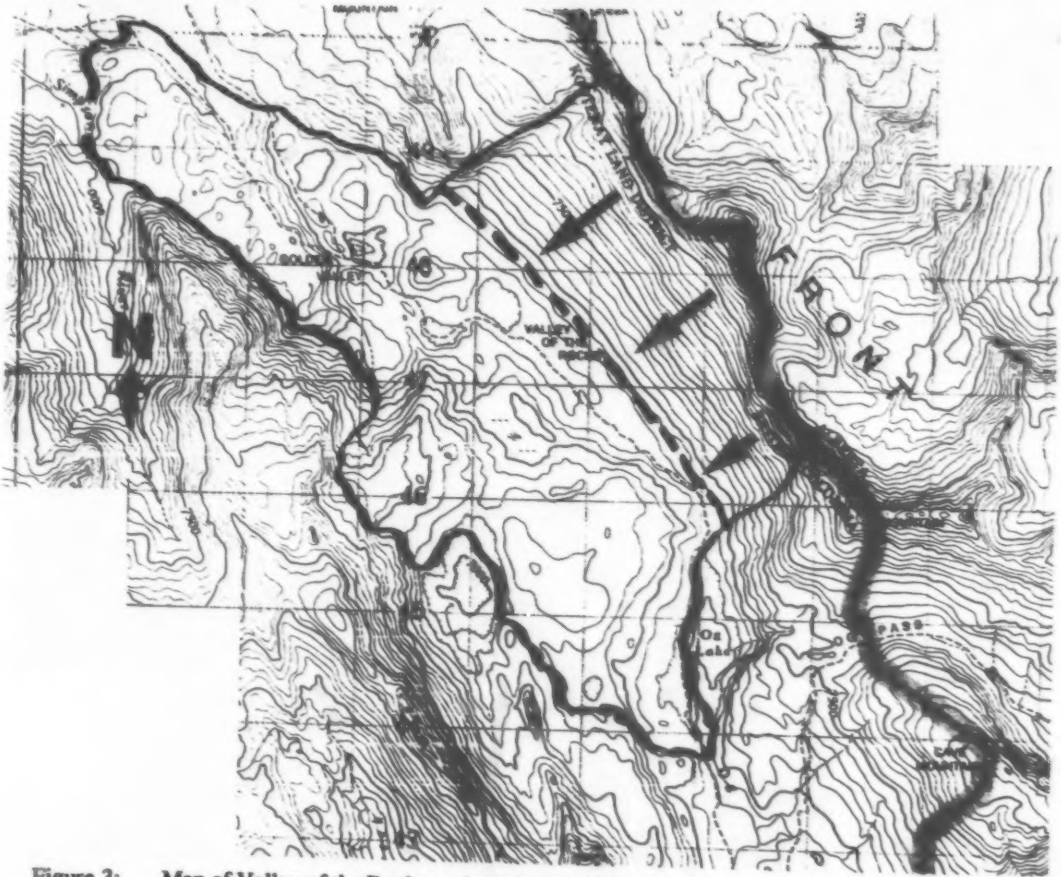


Figure 3: Map of Valley of the Rocks rock avalanche (82J/13). The squares are one square kilometre.

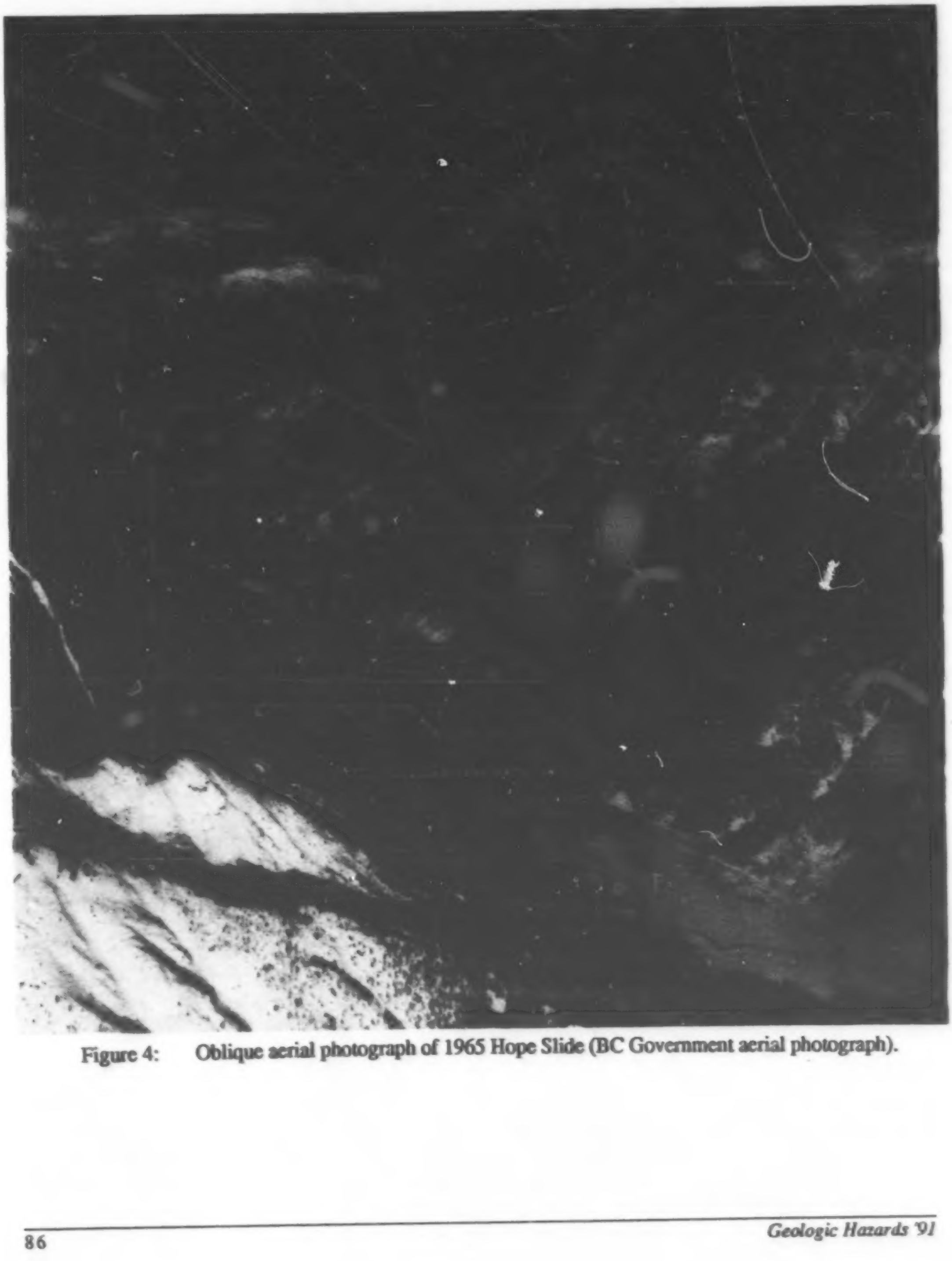


Figure 4: Oblique aerial photograph of 1965 Hope Slide (BC Government aerial photograph).

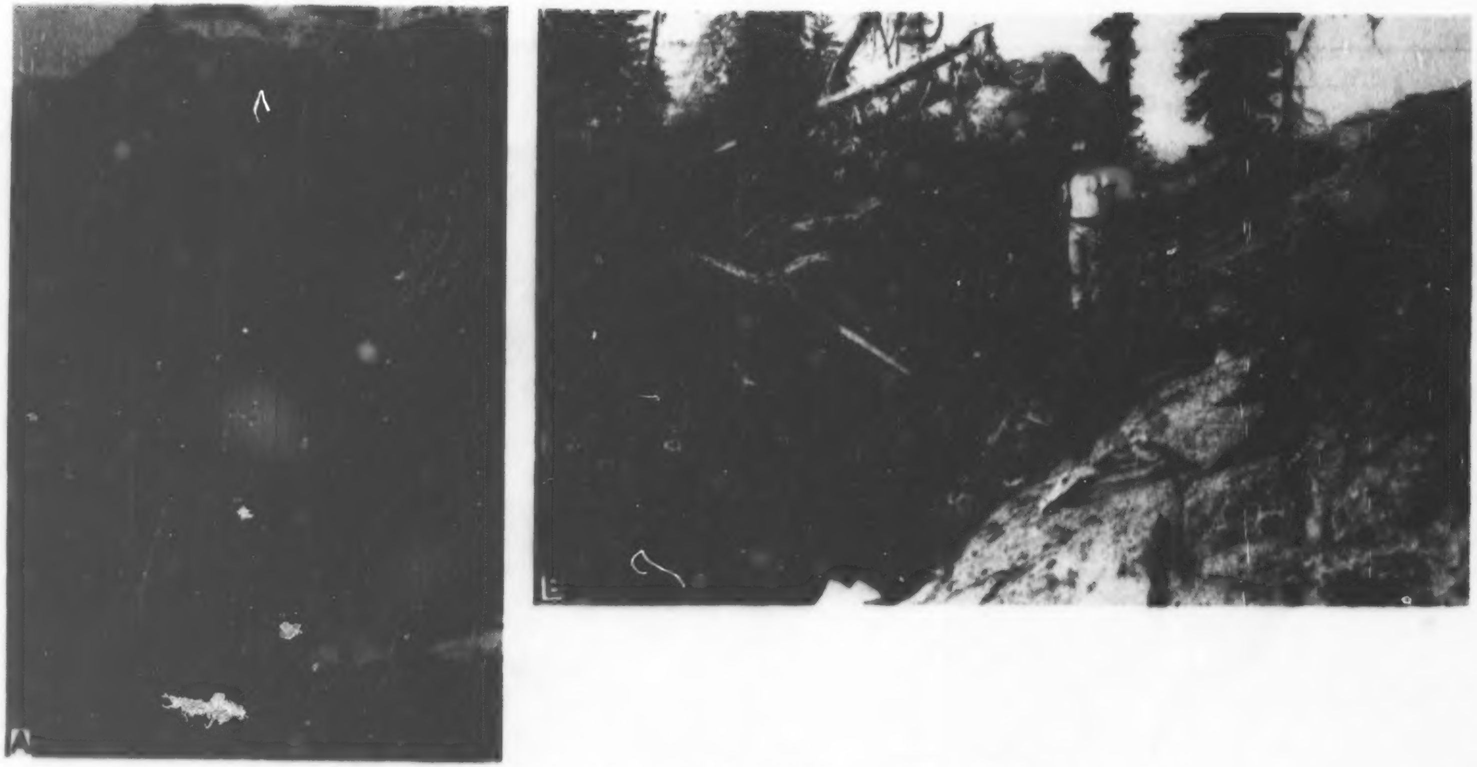


Figure 5: The prehistoric Mystery Creek rock avalanche, 20 kilometres northeast of Whistler. A) Oblique aerial view to the east. Toppling shown in B occurs on right hand (southern) margin of scar. B) Antislope scarp formed by toppling on southern margin of rock avalanche. Downslope to left.

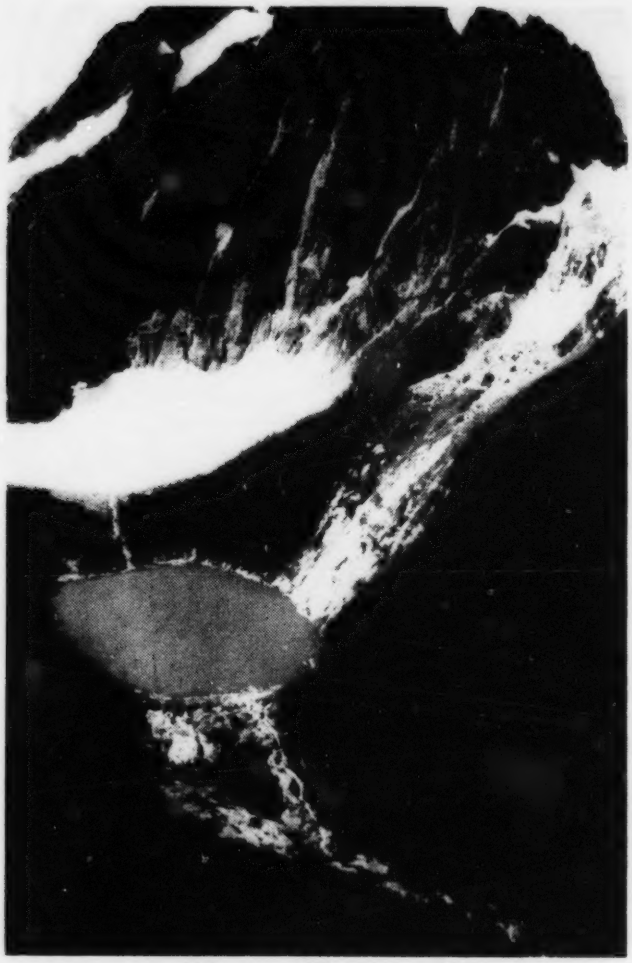


Figure 6: Oblique aerial photograph of 1946 Mount Colonel Foster rock avalanche. The rock mass detached from right hand peak of Mount Colonel Foster triggered by the Vancouver Island earthquake. As documented by Evans (1989) part of the debris descended into Landslide Lake and generated a displacement wave which destroyed forest in the Elk River valley.

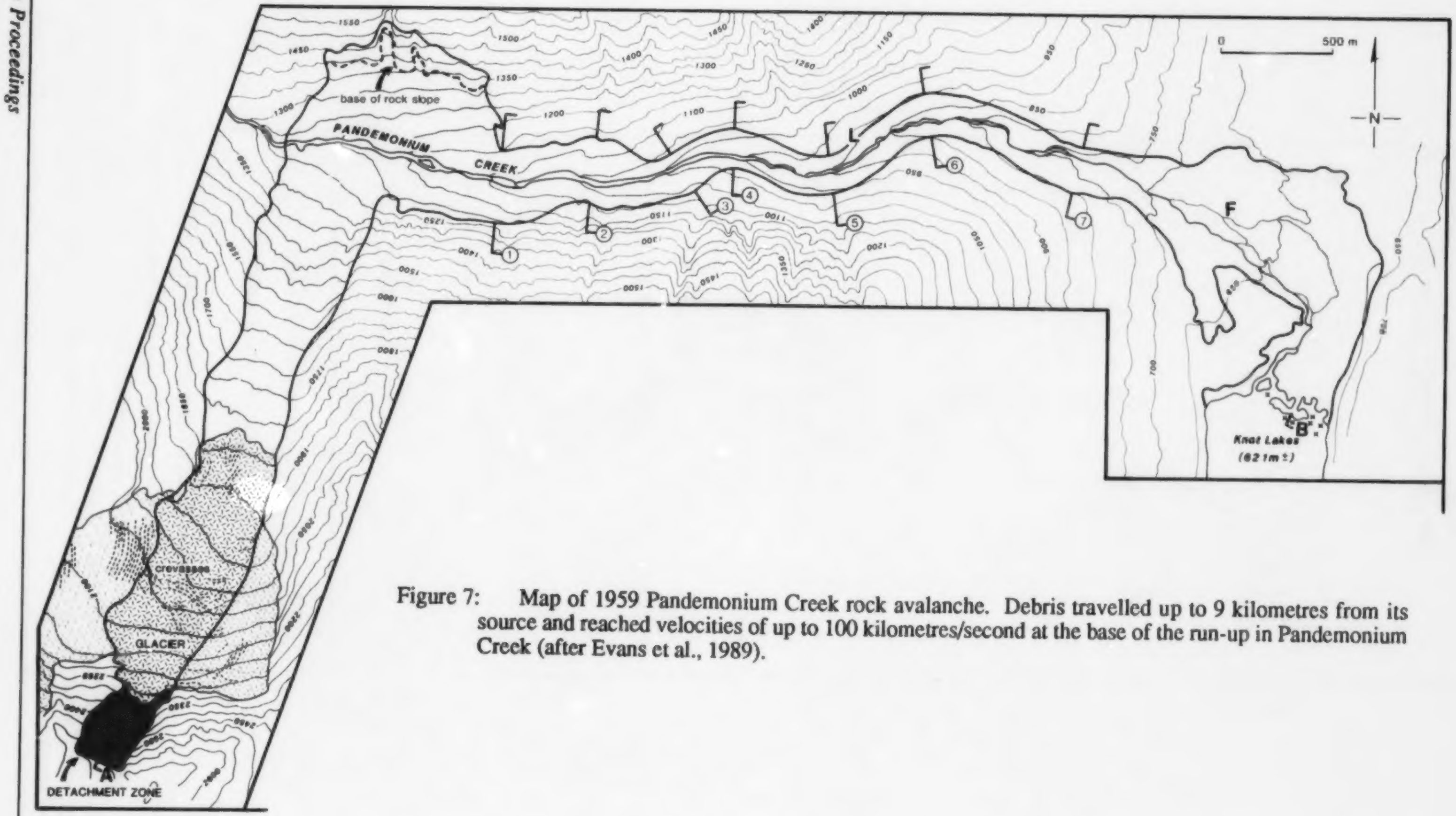

0
500 m
N
base of rock slope
PANDEMONIUM
CREEK
①
②
③
④
⑤
⑥
⑦
F
B
Knot Lakes
(821m±)
crevasses
GLACIER
A
DETACHMENT ZONE

Figure 7: Map of 1959 Pandemonium Creek rock avalanche. Debris travelled up to 9 kilometres from its source and reached velocities of up to 100 kilometres/second at the base of the run-up in Pandemonium Creek (after Evans et al., 1989).

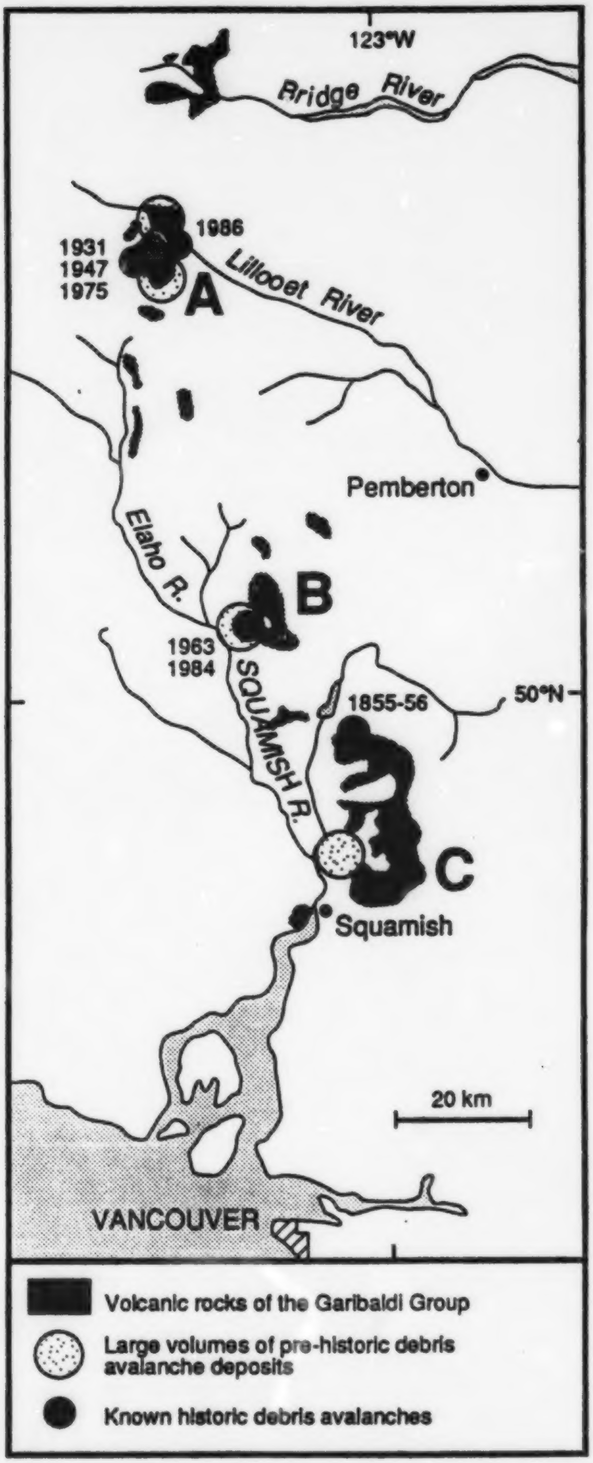
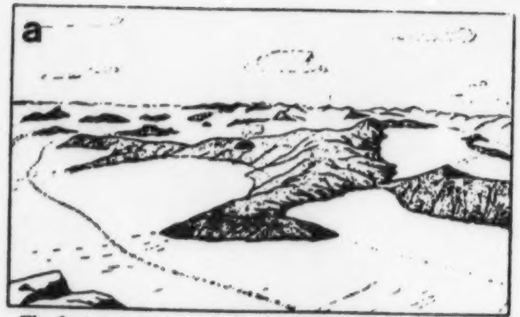
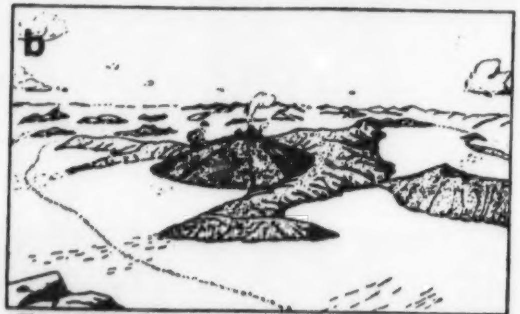

123°W
Bridge River
1986
1931
1947
1975
Lillooet River
A
Pemberton
Elaho R.
B
1963
1984
SQUAMISH R.
1855-56
50°N
C
Squamish
20 km
VANCOUVER
Volcanic rocks of the Garibaldi Group
Large volumes of pre-historic debris avalanche deposits
Known historic debris avalanches

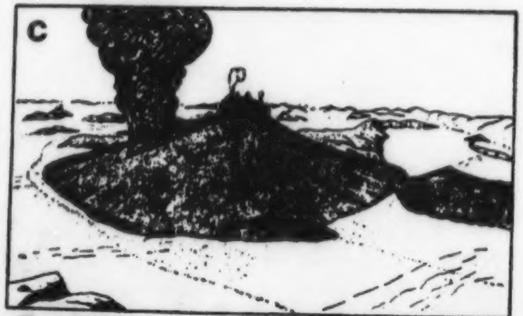
Figure 8: Map of Garibaldi Volcanic Belt, southwestern British Columbia showing main volcanic centres (A=Mount Meager, B=Mount Cayley, C=Mount Garibaldi), location of large volumes of prehistoric debris avalanche deposits and the location and dates of known historic debris avalanches (from Evans and Brooks, 1991).



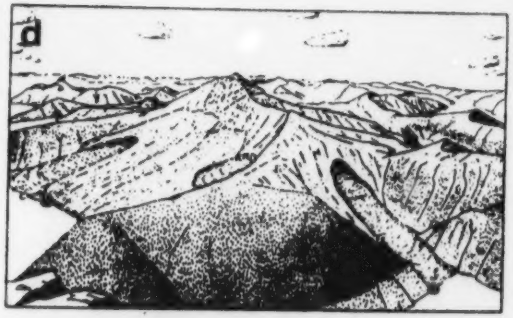
The first appearance of the plug dome of Mount Garibaldi shortly after the Wisconsin climax of the Cordilleran ice sheet.



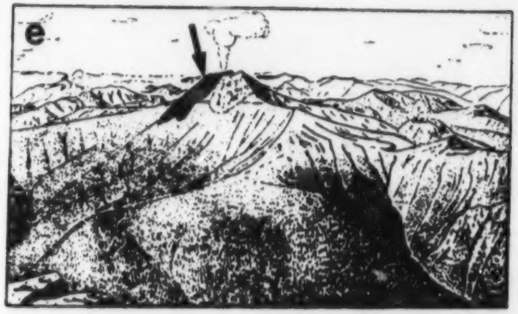
The tuff-breccia cone of Mount Garibaldi at an intermediate stage in its growth.



The tuff-breccia cone of Mount Garibaldi at a late stage in its growth showing a glowing avalanche and accompanying hot dust cloud sweeping down its western flank.



Mount Garibaldi during the period of rapid deglaciation showing the partial collapse of the tuff-breccia cone as a result of melting of ice beneath its western and southern flanks.



The final volcanic activity of Mount Garibaldi, with lava flowing from the north vent. Deglaciation and collapse of the tuff-breccia cone was essentially complete at this stage. Other volcanic activity taking place in the vicinity at about this time was centered at Clinker Mountain (left middle distance) and Opal Cone (right middle distance).

Figure 9: The evolution of Mount Garibaldi in the Late Pleistocene according to Mathews (1952a). Note that the flank collapse is hypothesized to precede the eruption of the Dalton's Dome lava flow (arrowed in e). Compare to Fig. 10.

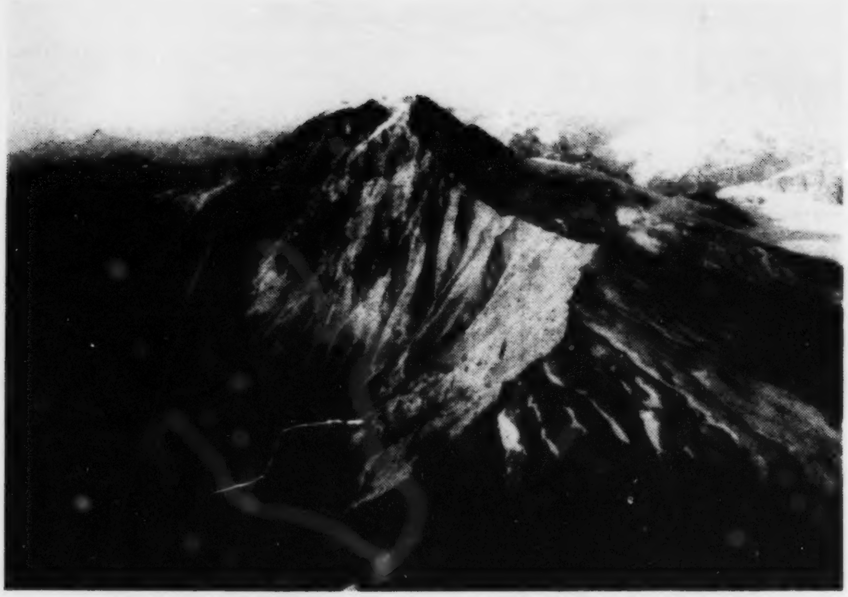


Figure 10: Oblique veiw of Mount Garibaldi viewed from the south. The steep western face of the volcano is essentially a scarp formed by the flank collapse illustrated in Fig. 9.

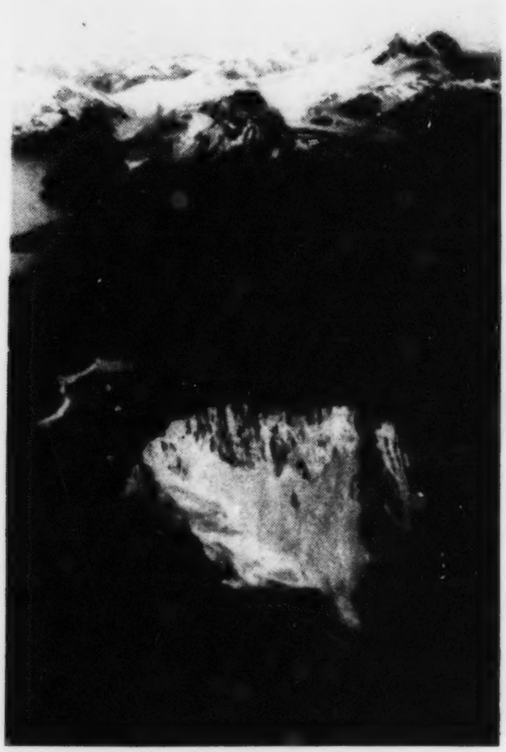


Figure 11: Aerial view of The Barrier, a steep rock face formed by the successive failure of the margin of the Clinker Peak lava flow, the most recent failure being the 1855-56 rock avalanche. Clinker Peak is visible as the obvious source of the lava flow. Mount Garibaldi is visible in the right background.

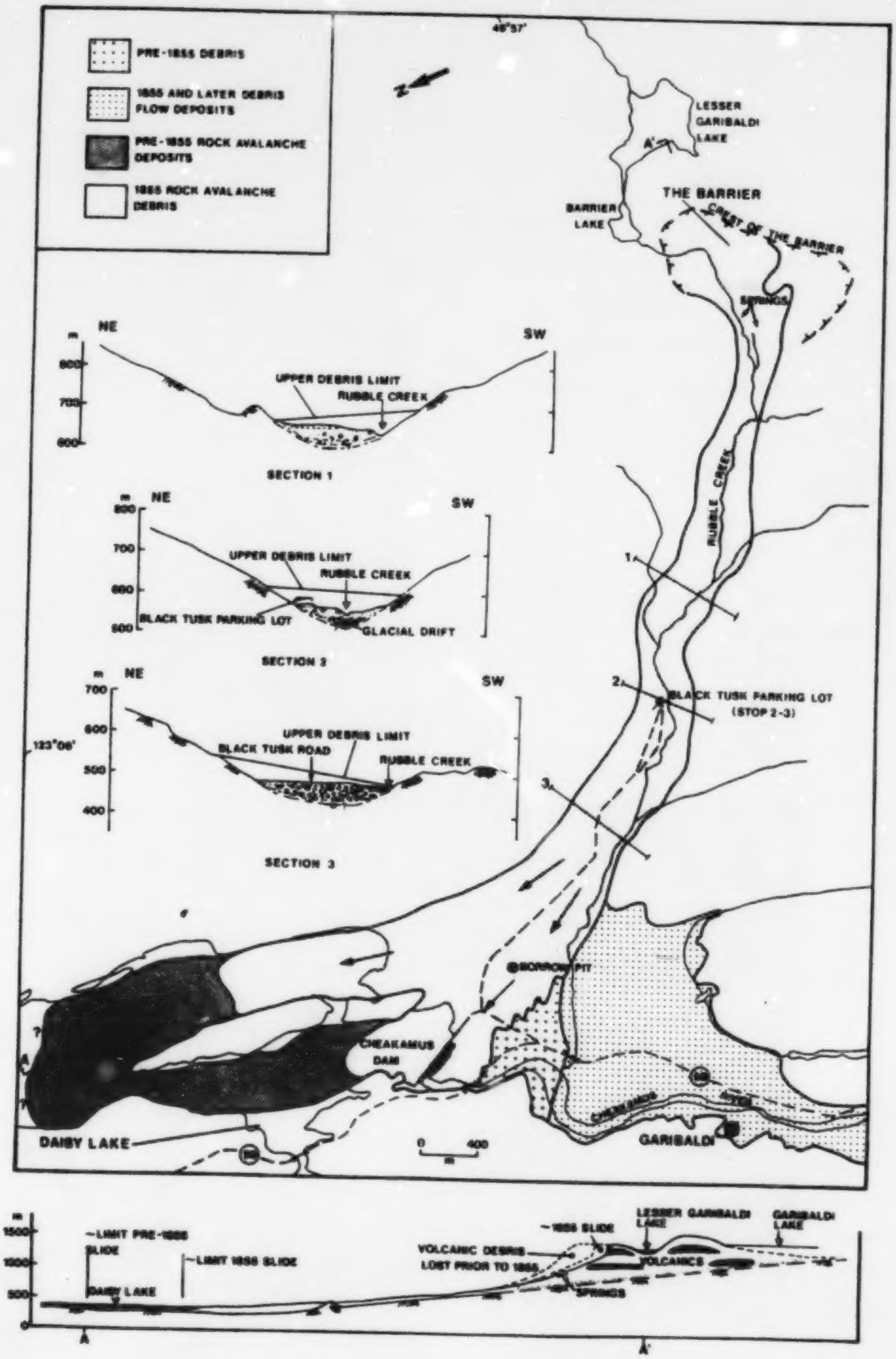

PRE-1855 DEBRIS
1855 AND LATER DEBRIS FLOW DEPOSITS
PRE-1855 ROCK AVALANCHE DEPOSITS
1855 ROCK AVALANCHE DEBRIS
N
49°57'
LESSER GARIBALDI LAKE
A'
THE BARRIER
BARRIER LAKE
CREST OF THE BARRIER
SPRINGS
NE
SW
m
800
700
600
UPPER DEBRIS LIMIT
RUBBLE CREEK
SECTION 1
NE
SW
m
800
700
600
500
UPPER DEBRIS LIMIT
RUBBLE CREEK
BLACK TUSK PARKING LOT
GLACIAL DRIFT
SECTION 2
NE
SW
m
700
600
500
400
123°06'
UPPER DEBRIS LIMIT
BLACK TUSK ROAD
RUBBLE CREEK
SECTION 3
RUBBLE CREEK
1
2
3
BLACK TUSK PARKING LOT
(STOP 2-3)
BORROW PIT
CHEAKAMUS DAM
DAISY LAKE
A
?
?
0
400
m
GARIBALDI
m
1500
1000
500
0
~LIMIT PRE-1855 SLIDE
~LIMIT 1855 SLIDE
DAISY LAKE
VOLCANIC DEBRIS LOST PRIOR TO 1855
~1855 SLIDE
LESSER GARIBALDI LAKE
GARIBALDI LAKE
VOLCANICS
SPRINGS
A
A'

Figure 12: Landslides in Rubble Creek, Mount Garibaldi volcanic complex; map, longitudinal profile, and cross-sections showing upper limit of debris (reproduced fromClague et al. [1987] which was redrawn from Hardy et al. [1978]).

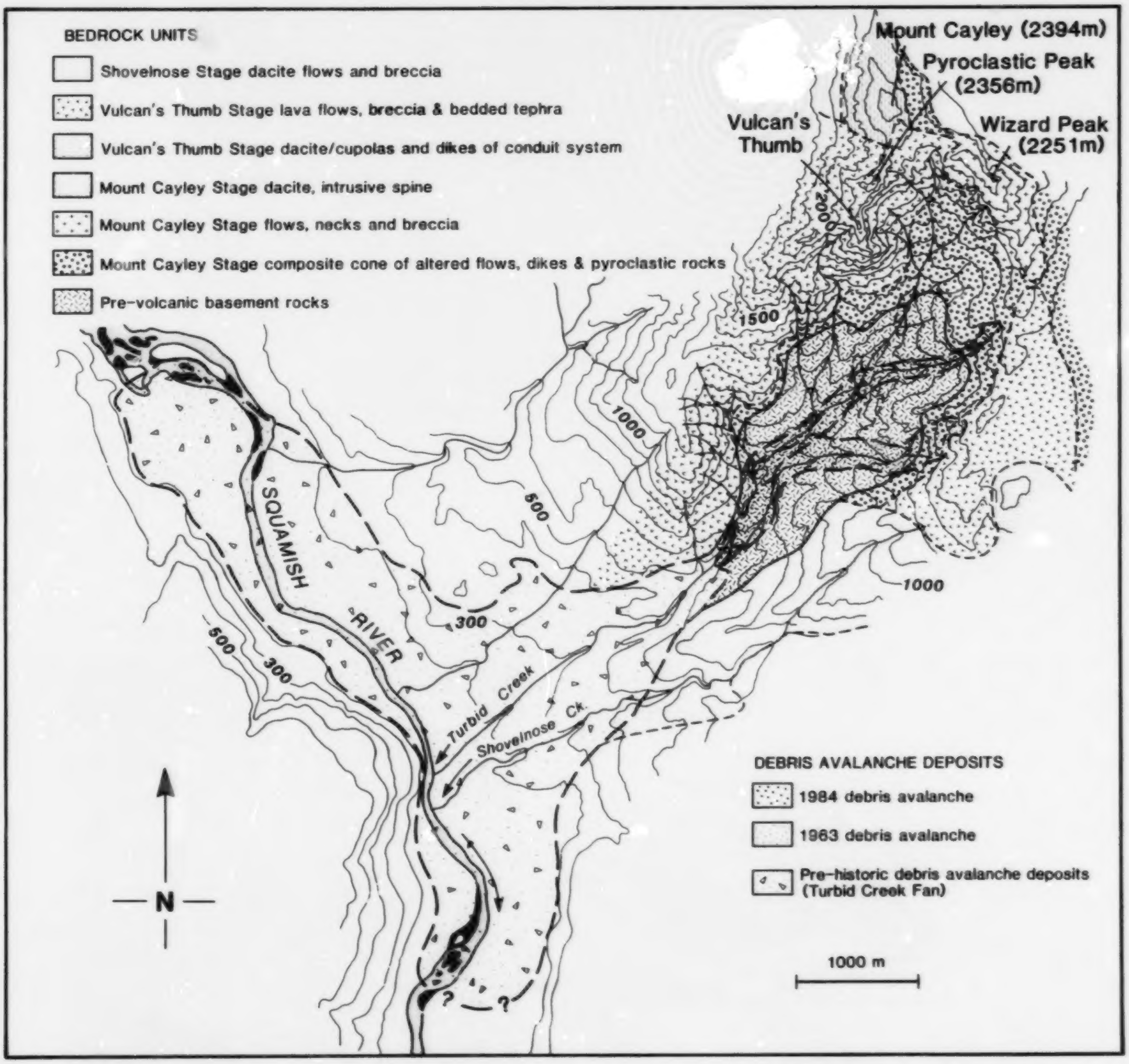

BEDROCK UNITS
Shovelnose Stage dacite flows and breccia
Vulcan's Thumb Stage lava flows, breccia & bedded tephra
Vulcan's Thumb Stage dacite/cupolas and dikes of conduit system
Mount Cayley Stage dacite, intrusive spine
Mount Cayley Stage flows, necks and breccia
Mount Cayley Stage composite cone of altered flows, dikes & pyroclastic rocks
Pre-volcanic basement rocks
Mount Cayley (2394m)
Pyroclastic Peak (2356m)
Wizard Peak (2251m)
Vulcan's Thumb
2000
1500
1000
500
300
1000
SQUAMISH
RIVER
500
300
Turbid Creek
Shovelnose Ck.
DEBRIS AVALANCHE DEPOSITS
1984 debris avalanche
1963 debris avalanche
Pre-historic debris avalanche deposits (Turbid Creek Fan)
1000 m
N
?
?

Figure 13: Map of the Mount Cayley area showing the geology of Turbid Creek basin (after Souther, 1980), limit of prehistoric debris avalanche accumulation and historic debris avalanche paths (after Evans and Brooks, 1991).

Figure 14: Aerial view of 1984 debris avalanche on the western slopees of Mount Cayley volcano. Also visible is the source (A) of the 1963 debris avalanche. Both landslides involved Pleistocene pyroclastic rocks.

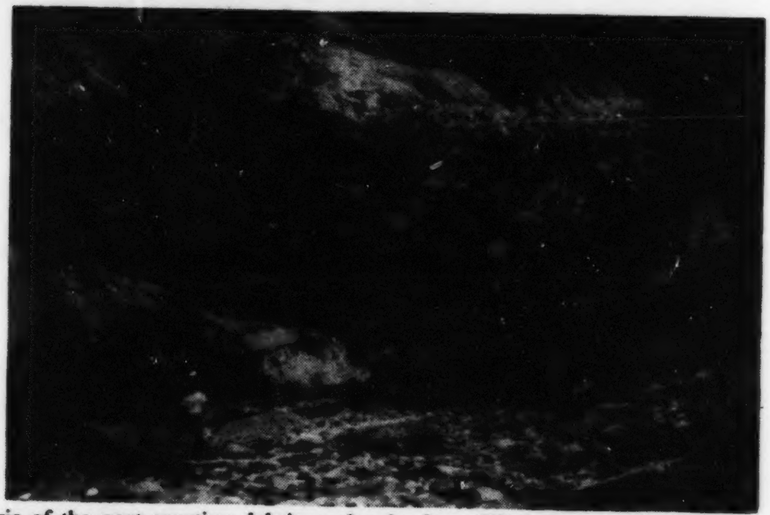


Figure 15: Debris of the post-eruption debris avalanche from Plinth Peak, Lillooet River valley, Mount Meager volcanic complex. Note figure for scale.

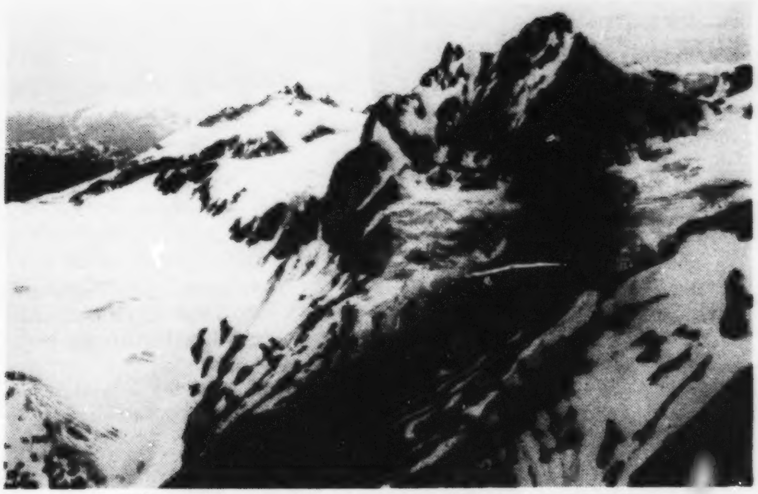


Figure 16: Aerial view of 1986 rock avalanche from the peak of Mount Meager.

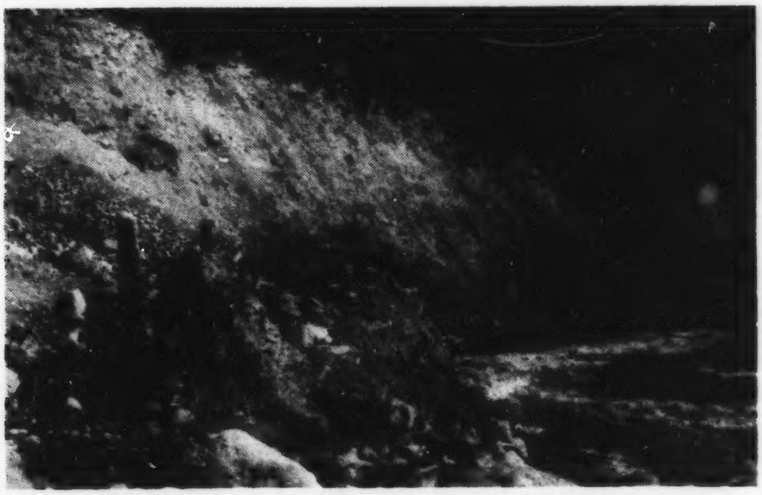


Figure 17: Trees in growth position buried by prehistoric debris avalanche in Devastation Creek. Wood recovered from these trees by P. Jordon (figure at left) yielded a C14 age of 2170 ± 70 years BP (GSC-4302).

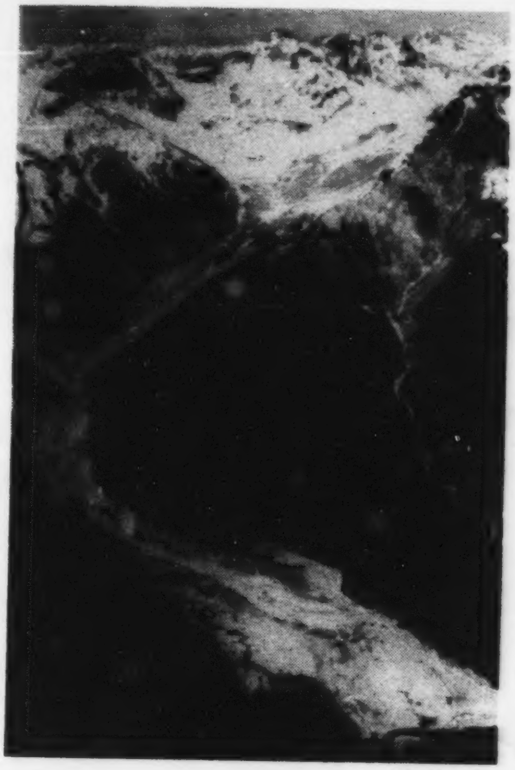


Figure 18: Aerial view of 1975 Devastation Glacier debris avalanche. The landslide involved 13 million cubic metres and originated in laltered Pleistocene pyroclastic rocks on the western flank of Pylon Peak. The landslide killed four people.

Figure 19: Aerial view of 1888 Ashcroft landslide. The landslide involved approximately 15 million cubic metres of Pleistocene glaciolacustrine sediments and blocked the Thompson River (flowing to bottom right) for 44 hours.

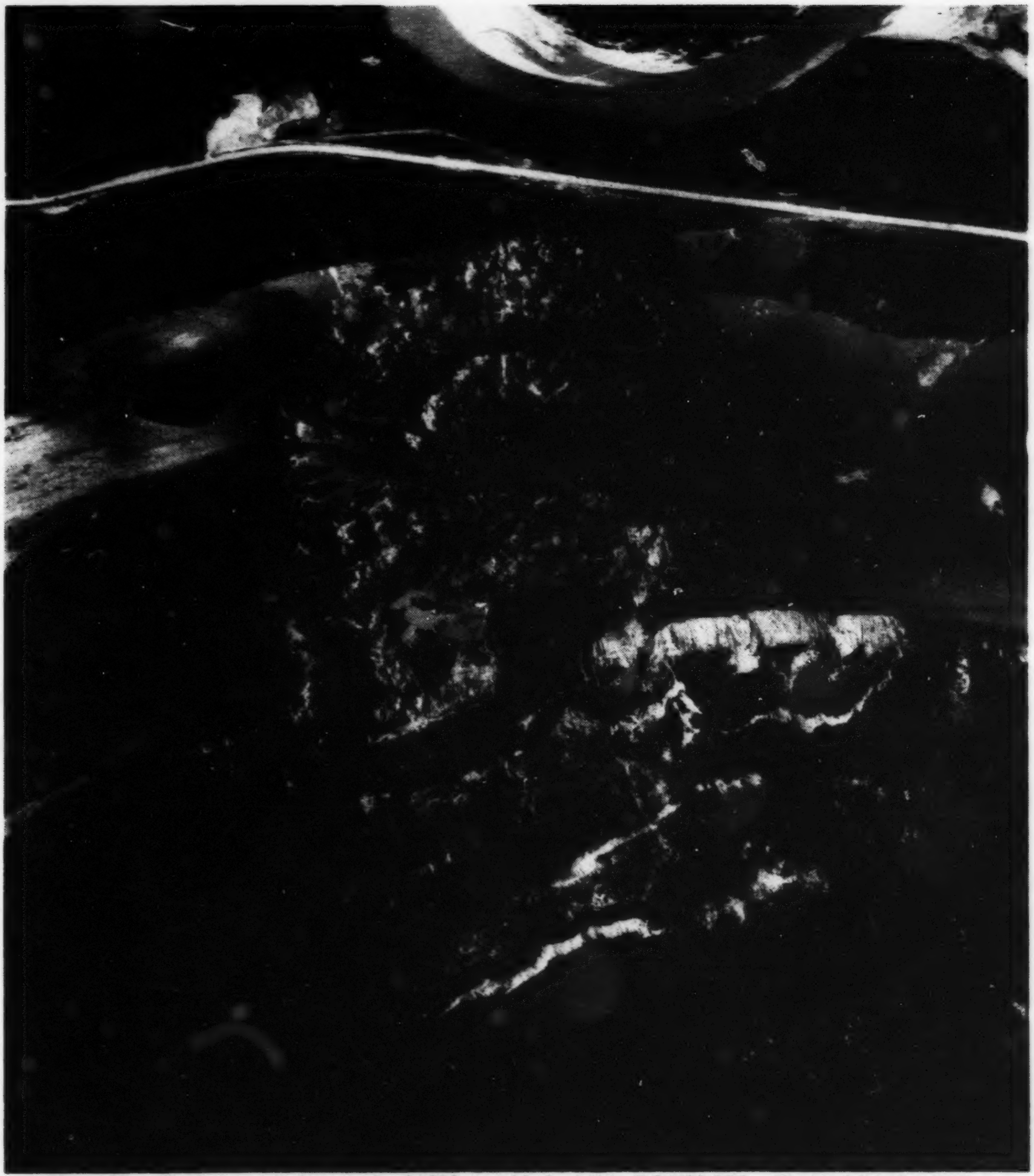


Figure 20: Vertical aerial photograph of 1973 Attachie landslide (BC5529-075). The landslide involved approximately 24 million cubic metres of Pleistocene glaciolacustrine sediments and temporarily blocked the Peace River.

LOW MAGNITUDE/HIGH FREQUENCY MASS MOVEMENTS

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"If we want or have to live in the mountains, then we also have to accept the danger" from *Landslides and Human Lives* (Heim, 1932, translated by Skermer, 1989).

ABSTRACT

Low magnitude mass movements usually involve less than 1 million cubic metres of material. Numerous low magnitude events occur in British Columbia each year, and are therefore referred to as high frequency. Common types of low magnitude/high frequency (lm/hf) mass movements include rock falls; rock, debris and earth slides; debris flows and torrents; and snow avalanches. The causes of such mass movements include natural causes such as steep terrain, climatic factors, and seismicity, and increasingly activities of Man. Mass movements can occur anywhere in the province where appropriate conditions exist.

The occurrence of lm/hf mass movement leads to the loss of natural resources, causes physical disruptions and economical hardships for many people in the province, and unfortunately results in several deaths each year. In addition to their impact on many individuals, numerous government agencies and companies are directly or indirectly affected by these events. These agencies include the provincial ministries of Transportation and Highways, Environment, Forests, and Municipal Affairs; federal Fisheries and Oceans, Forests, and Parks Canada; regional districts and municipalities; and even the Workers' Compensation Board. Companies that are directly affected include transportation and utility companies. The tourist industry is also affected, usually indirectly.

In British Columbia, research assessments and investigations of lm/hf mass movements are being carried out by a diverse cross section of agencies and individuals. These include a few provincial ministries and federal departments, a few of the larger companies, several university researchers and a number of consultants. In the past, most of this work has been carried out reactively -- that is studying mass movements that have occurred. In the past decade, however, more proactive studies have been initiated.

At the present time, the level of general knowledge with regard to the causes, affects and methods of mitigation of lm/hf mass movements in the province is relatively high. Several British Columbian agencies and individuals are recognized as world authorities. As development of the province continues to move into more remote and mountainous terrain, however, the impact of mass movements on the people and resources of the province will increase. Additional research is therefore warranted.

Research, assessments and investigations of lm/hf mass movements in British Columbia are suffering from a number of major problems. These include a lack of a provincial "natural hazards policy" and a lack of a provincial body to co-ordinate studies. This has resulted in a lack of adequate funding for research, random rather that systematic assessments and investigations, and an emphasis on reactive studies. One suggestion to assist future studies of lm/hf mass movements, along with other forms of natural hazards, is the establishment of a joint federal/provincial institute for natural hazards research.

INTRODUCTION

What is meant by low magnitude/high frequency (lm/hf) mass movements?

- "A landslide is the movement of a mass of rock, earth or debris down a slope" (Cruden, 1990),
- <1,000,000 cubic metres of material, approximately 10 cubic football fields,
- numerous events occur annually,
- some types of events occur repeatedly at the same location,
- perhaps not as spectacular as high magnitude/low frequency mass movements, but much more of a day to day problem.

CLASSIFICATION

- refer to Varnes' (1978) classification of landslides shown in Table 1,
- in 1992 Dave Cruden, University of Alberta, will be updating this classification for US Transportation Research Board,
- broadly speaking lm/hf mass movements can be divided into 3 types:
  - rockfalls (Figures 1 and 2)
  - rock, debris, earth slides (Figures 3 nd 4)
  - debris flows, these also include erosion along creeks (Figures 5 and 6)
- refer to Japanese landslide problem
- two other types:
  - snow avalanches: 1/2 occur in National Parks, more people in BC have been killed by snow avalanches than all other forms of mass movement combined
  - underwater mass movements: we are just finding out about these, e.g. 1975 Kitimat Slide, $500,000 in damage

-debris flows, debris torrents and snow avalanches often reoccur in the same location, or putting it another way, falls and slides usually have a much longer return period than flows and snow avalanches.

MASS MOVEMENT EVENTS

Between 1855 and 1983, 84 damaging landslide events (not counting snow avalanches) occurred (Evans and Clague, 1988)

- 44 per cent debris flows
- 36 per cent slides
- 20 per cent rockfalls (16% <1 million cubic metres in volume).

Recent examples in past year:

Slocan Valley: 4 debris flows torrents, May 1990
-associated with logging
-blocked the highway in 4 locations, destroyed small hydro plant, water supply, went on both sides of a residence

Joe Rich Subdivision:
- debris avalanche/flow, June 1990
- 3 people killed, 1:100 to 1:400 year storm event, no known geological evidence or history of previous events
- associated with logging

Enderby:
- 61 debris avalanches/flows, June 1990
- same storm as Joe Rich, 12 tracks reached the highway
- no deaths, but just lucky

Howe Sound rock fall:
- October 1990, 10 000 cubic metres
- will discuss in more detail later in presentation
- it is just not coincidence that Hoek and Brey (1981) used a photo of a Squamish Hwy rockfall as their cover

Dorothy Creek debris slide:
- Great Central Lake, November 1990
- 1 life lost, because of this slide, WCB is considering establishing a "limiting rainfall" above which logging activities would be suspended

Tofino Creek rockfall:
- January 1991, 15 000 to 25 000 cubic metres
- destroyed 500 metres of new forestry road and just about killed excavator operator

This past winter alone, up to the present, there has been 1600 avalanches in the province, a number of which have interfered with man.

CAUSES OF MASS MOVEMENTS

Steep terrain

- glaciation is major cause of this steep terrain in B.C., and we build roads, railways and houses in these areas

Climate

- rainfall, snowfall, antecedent rainfall, rain on snow, freezing levels,
- "climequakes" (Skermer, 1985): sudden changes in a gradual changing climatic pattern, for example a wetter than normal early 1980's, perhaps this past fall

Geology

- some rock and soil is more susceptible to mass movement than others

Seismicity

- for example, 1946 Vancouver Island earthquake

Table 1. Classification of Landslides (after Varnes, 1978).

TYPE OF MOVEMENT	TYPE OF MATERIAL		
	BEDROCK	DEBRIS (COARSE SOIL)	EARTH (FINE SOIL)
I FALLS	rock fall	debris fall	earth fall
II TOPPLES	rock topple	debris topple	earth topple
III SLIDES - ROTATIONAL	rock slump	debris slump	earth slump
III SLIDES - TRANSLATIONAL	rock block slide rock slide	debris slide	earth slide
IV SPREADS	rock spread	-	earth lateral spread
V FLOWS	bedrock flow (sackung)	debris flow debris avalanche block stream solifluction soil creep	wet sand flow rapid earth flow earth flow loess flow dry sand flow
VI COMPLEX	rock fall-avalanche	slump-earth flow cambering	-

Overlay maps of relief, annual precipitation, geology, and seismicity will show you where there is the greatest potential for mass movements

Influence of man

- removal of support (undercutting)
    -Hell's Gate, Squamish Highway, almost all construction on a steep slope, mining activities
- addition of surcharge (filling)
    -cut and fill roads, mine waste, valley fills
- changes in slope and/or drainage conditions
    - logging, fire, disease, windthrow
    - road building and placement of culverts to change water patterns
    - irrigation (in Interior)
    - infilling of valleys by mine waste
    - creation of reservoirs

- you can usually find a natural analog of these effects, but man accelerates natural processes.

IMPACTS OF LOW MAGNITUDE/ HIGH FREQUENCY MASS MOVEMENTS

Loss of resources

- loss of land
- merchantable timber
- ore
- fish and sea life due to sedimentation
- esthetics

Physical disruptions

- transportation routes: roads, railways, pipelines, fibre optics cable

- power transmission lines, dam sites, reservoirs
- residential areas
- other structures such as wharfs, buildings, services (water, sewer, gas)

Impact on man
- disruption to normal patterns (nuisance factor)
- injury, trauma, loss of life
- between 1855-1983: 345 lives lost, 75 per cent due to low mag/high freq events (does not include snow avalanches) (Evans and Clague, 1988)
- small potatoes when compared to the number of lives lost in motor vehicle accidents each year in B.C.
- must consider voluntary vs involuntary risks

ECONOMICS

- economic losses result from all of the above impacts
- difficult to find a per year costs, changes dramatically from year to year

Reactive costs
- e.g. Howe Sound rockfall, October, 1990
- direct: impact on road and railway, maintenance and construction costs
- indirect:
    - -disruption in road and rail traffic, commercial and individual, economic and stress
    - -loss of revenue at Squamish/ Whistler/Vancouver vs additional revenue
    - -extra trains, ferry costs
    - -almost loss of life
    - -Darcy Lake Road, paving 1991

Proactive costs
- broken down into passive mitigation and active mitigation
- it is difficult to put a cost saving on a passive mitigative work
- active mitigation can be subdivided into retrofitting and new work
- retrofitting (Cruden *et al.*, 1988)
    - e.g. 1983-1984: $480,000 spent on rock scaling along Highway 99 (Squamish Highway), $20 million in debris flow defences
    - e.g. 1971-1985: $28 million on rock stabilization on CNR between Hope and Kamloops
- new works (Cruden *et al.*, 1988)
    - e.g. Coquihalla 1984-1985 Phase 1, $1.1 million on debris flow defenses.

AGENCIES/GROUPS AFFECTED AND THOSE INVOLVED IN STUDYING MASS MOVEMENTS (indicated with a *)

***BC Ministry of Highways**
*Construction, Maintenance, Geotechnical Branches, districts, regions and headquarters
*Subdivision approvals
*Snow avalanches section

***BC Ministry of Environment, Lands and Parks**
Water Management
*Surficial Geology (Fisheries, Habitat Management)
- this program is dwindling away to nothing

*Water Controller, Dam Safety

BC Minsitry of Forests
*Operations, planning, approval
*Research, Fish-Forestry Interactive Program among other research

***BC Ministry of Energy, Mines and Petroleum Resources**
*Environmental Geology Section, Surficial Geology Unit
*Mine Inspectors

BC Municipal Affairs, Culture and Recreation
Inspectors of Municipalities
Parks

BC Solicitor General
Provincial Emergency Program

Regional Districts and Municipalities

***BC Hydro** (reservoir shorelines, dam and power sites, transmission lines)

***BC Tel** (overhead, buried, fibre optics cable)

***Canada Energy Mines and Resources**
*Geological Survey of Canada (Ottawa, Vancouver)
*Pacific Geoscience Centre (Sidney, the only group that is studying underwater landslides)

***Canada Fisheries and Oceans**
Fish Forestry Interactive Program (FFIP)

***Canada Forestry**
Fish Forestry Interactive Program (FFIP) and minor additional research

NRC snow avalanche (this program is being terminated at the end of March 1991)

National Parks

Workers' Compensation Board of BC
Companies
transportation: *CP, *CNR, truck and bus transportation
resource: *forestry, *mines, fisheries, tourism

***Universities**
*UBC: Geography, Geological Engineering, Civil Engineering
*Simon Fraser: Geography
*Univ. of Alberta: Civil Engineering and Geology

***Consultants**
*Companies: Thurber, Piteau, Golder, Klohn Leonoff, SRK
*Individuals

LOCATION OF WORK

Hit and miss research, varies, depends upon where development and other research is being done, not systematic
- Reactive, where slides have occurred
- Proactive, where slides have occurred
- Proactive, where slides have occurred in past, hazards recognized, property, life at risk, or may be at risk.

MAJOR PROBLEMS

1. As the population of B.C. increases, and the natural resources become scarcer, we move, work and travel in areas of steeper terrains, and are therefore putting ourselves at more risk from mass movements.

2. There is an obvious lack of awareness.

3. We are slowly gaining the knowledge and technology how to live and deal with landslides. Past research, however, has been generally hit and miss, not systematic, and with some exceptions, reactive. In the past decade some proactive work has been undertaken (e.g. Coquihalla Highway).

The following comments relate to all natural/geologic hazards:

1. There is no natural hazards policy in province.
   -reference to Association of Professional Engineers of BC 1976 and 1983 attempts:
   "British Columbia is subject to a number of natural hazards which make parts of it moderately dangerous to live in. Although it could be argued that those who choose to live in places subject to natural hazards such as avalanches, landslides and floods, should be prepared to suffer the consequences, in practice people usually are not aware of the risks...there is a legitimate public interest in minimizing potential damage and loss of life due to natural hazards. We believe that, following the spirit of our (the Association of Professional Engineers of B.C.) code of ethics, the Association should push for and offer its help to the Government in establishing a Provincial Natural Hazards Policy." (Farquharson *et al.*, 1976). (refrain of Albert Heim)
   - 1979 Land Titles Act and 1985 Municipal Act and Bylaws have helped the situation somewhat

2. There is no provincial coordination in the area of geological hazards (a data base would be a good start), there is a lack of funding for proactive research, there is a decline of basic surficial geological mapping by MOE, a pull out of federal funds in the area of snow avalanche research.

SOMETHING TO CONSIDER

What about a joint provincially/federally funded institute (centre) for natural hazards?

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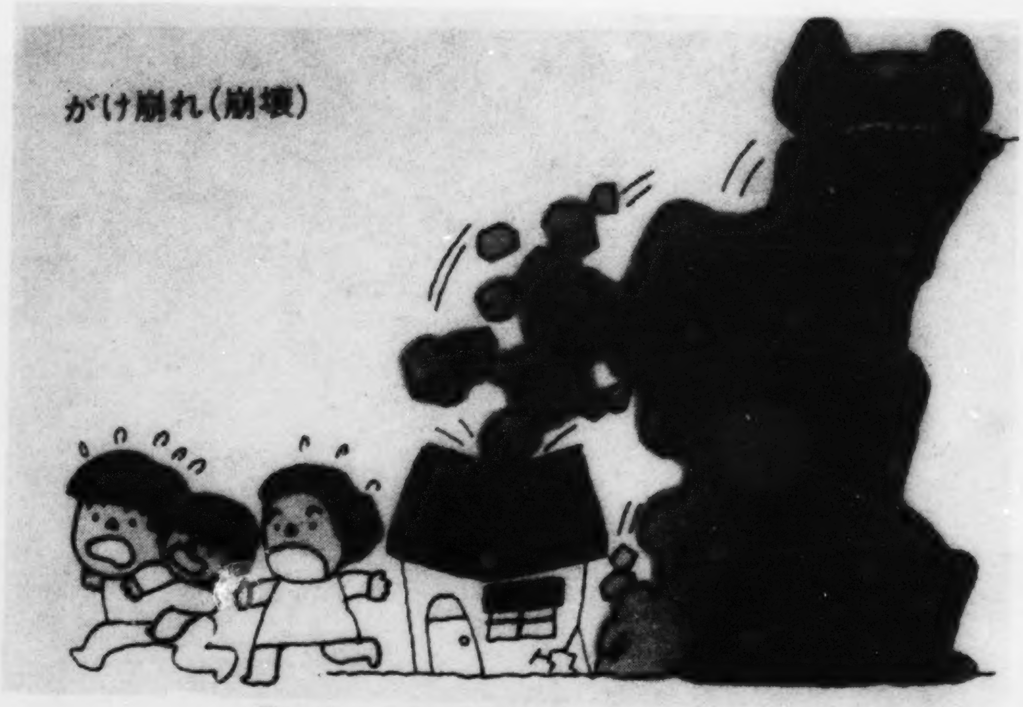

Figure 1: Japanese cartoon of rockfall hazard.

Figure 2: Howe Sound rockfall, October 1990.

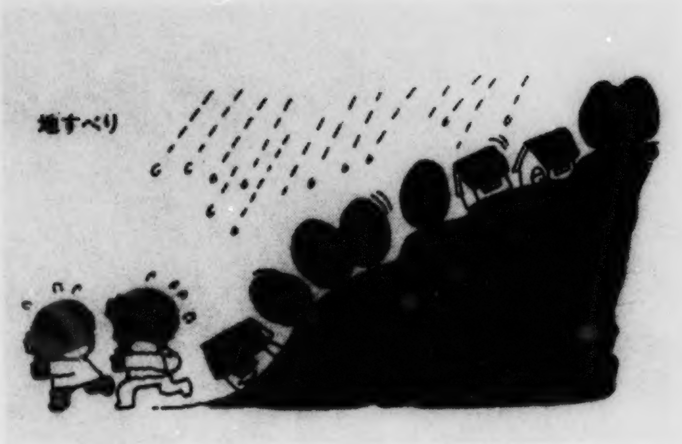

Figure 3: Japanese cartoon of landslide hazard.

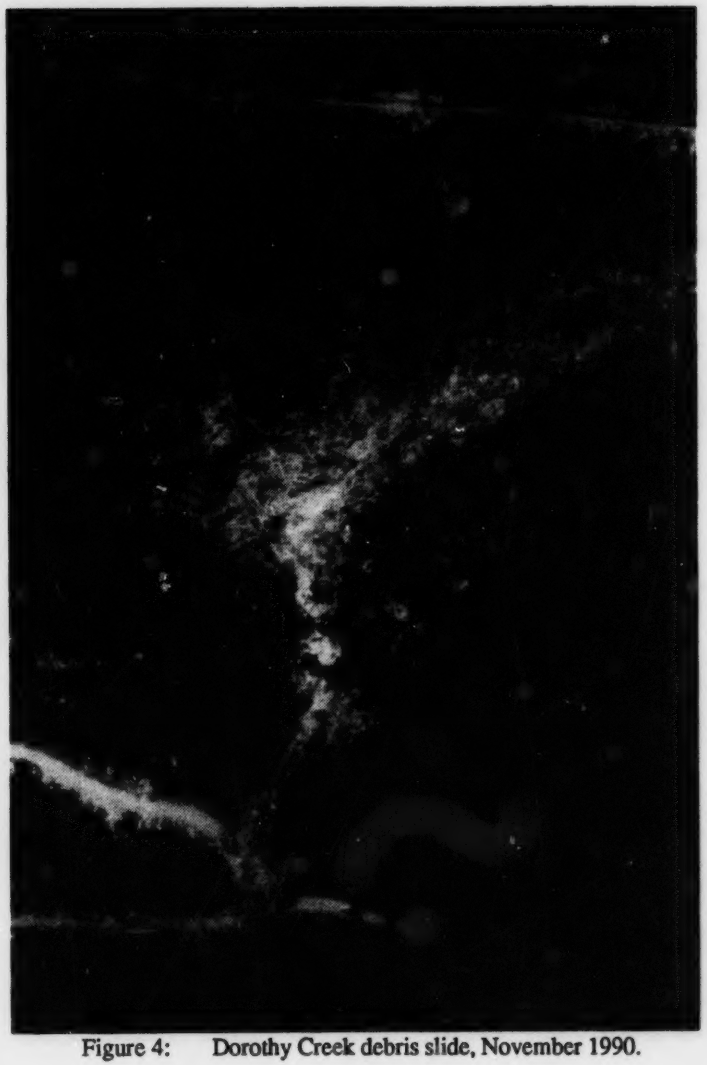

Figure 4: Dorothy Creek debris slide, November 1990.

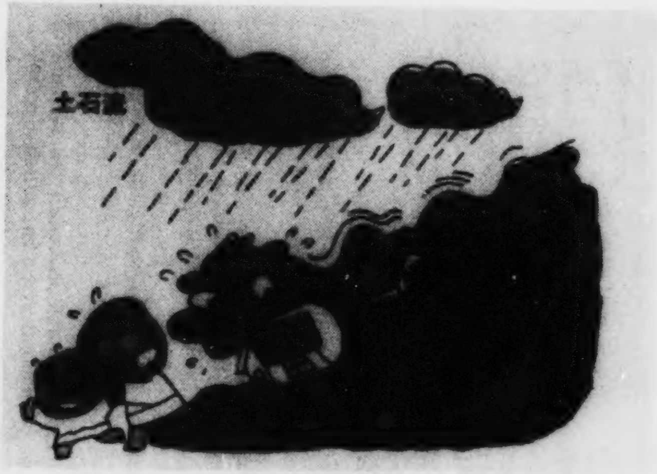

Figure 5: Japanese cartoon of debris flow hazard.

Figure 6: Alberta Creek channelized debris flow, February, 1983.

THE ROLE OF THE PROVINCIAL EMERGENCY PROGRAM IN GEOLOGIC HAZARDS MANAGEMENT AND MITIGATION

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PEP RESPONSIBILITIES

1) Provide a leadership role in emergency planning for the provincial government and its agencies. This involves the status of plans, their content, standards and specifications, training in preparing plans and the coordination of planning through the "Interagency Emergency Preparedness Committee" (IEPC).

2) Provide advice and assistance to regional and municipal governments in emergency planning. This involves development of standards, assistance in exercising plans and in training for writing and exercising plans.

3) Provide advice and assistance to industry in emergency preparedness.

4) Create public awareness of the need for preparedness.

5) Coordinate provincial assistance in responding to an emergency. This includes notification, assessment of need, logistical support, communication and public information. Direct operation for those emergencies which are not assigned to another ministry of government.

6) Establish, maintain and operate the government's "Emergency Operations Centre" (EOC) for major emergencies.

7) Provide emergency preparedness training for provincial government staff, municipal officials, volunteers and the public.

8) Administer the Disaster Financial Assistance Program.

9) Support the Canadian Armed Forces and Police in search and rescue through the use of trained volunteers.

10) Support emergency services volunteers. This includes search and rescue, PEP air service, amateur radio and emergency social services (approximately 7,400).

PEP COMMITMENT

Through the PEP, the province's commitment to emergency preparedness is illustrated by the fact that over 2 1/4 million dollars a year is allocated to preparedness and initial response to emergencies and disasters. In addition to this 2 1/4 million dollars, the province, through the PEP has allocated 52.4 million dollars for Disaster Financial Assistance this fiscal year.

PROVINCIAL BENEFITS

In addition to promoting emergency preparedness to the general public by such means as pamphlets, information pages on earthquakes and tsunamis located in the phone book, the PEP participates in conferences and workshops such as the Geologic Hazard Workshop.

The PEP actively promotes the Joint Emergency Preparedness Program (JEPP). JEPP is a cost sharing program by which municipal and provincial agencies can access federal funding of up to 50 per cent, for approved emergency preparedness projects.

The PEP has been successful in having April 22-27, 1991 proclaimed "Emergency Preparedness Week". All levels of government, industry and individuals were encouraged to participate.

CONCLUSION

The Ministry of Solicitor General and the PEP are committed to emergency preparedness at all levels of government, industry and at the individual and family level. With your continued support and commitment, the level of emergency preparedness in British Columbia will continue to improve.

THE FLOOD HAZARD

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ABSTRACT

Floods originate from meteorological events which give rise to the excursion of water into areas not normally inundated. The source of flood waters may be hydrologic or oceanographic, leading to three basic types of flooding: coastal, river or "local".

The flood hazard is the threat of economic loss, or loss of life. Funds allocated to repair damage caused by the 1990 floods in British Columbia were $32.4 million, as compared to $177 million in damage, in 1990 dollars, caused by the Fraser River flood in 1948. Damage caused in Port Alberni by the 1964 tsunami was estimated at $4.7 million, in 1990 dollars.

Coastal flooding is driven principally by either tsunami or storm surge events. The extent of the tsunami flood hazard is related to type, frequency and location of seismic or landslide events, coupled with any potential for sympathetic response of the adjacent water body to the impulsively-generated wave.

Storm surges, which give rise to water levels exceeding normal astronomical tides, are caused by winds driving waters shoreward and are often coupled with low pressure systems, which give rise to slight increases in sea levels. Contemporary landforms developed by coastal processes, such as deltas, spits, and backshore areas, are most vulnerable to storm surge flooding. Island View Beach on Vancouver Island, the West Vancouver foreshore and Boundary Bay are a few of the local areas that have experienced coastal flooding. The heavily populated area of Lulu Island is provided protection against both coastal and river flooding. Flooding from rising sea levels remains a potential concern but not a proven threat.

River floods characteristically fall into one of two categories: snow melt events or rainfall events. The large river basins produce peak flows in the late spring as a result of snow melt, therefore the magnitude of the flood flow depends upon the amount of snow pack and also the meteorological conditions during the snow melt. Characteristic of the snow melt floods in major drainages is that the flood duration may be measured in days or weeks, rather than hours as is the case for smaller drainages or coastal flooding events.

Rainfall events tend to cause quicker "flashy" floods, either due to storms of intense rainfall, such as would occur at Dawson Creek or in the Okanagan, or due to rain-on-snow events where a warming trend and rainfall follows a shallow accumulation of snow. The major floods associated with coastal streams are typically associated with rain-on-snow events in November-December, as occurred during November 1990 on the Chilliwack River. Snow melt floods are generally easier to monitor and forecast than rainfall-induced floods.

As is the case for coastal flooding, the areas most vulnerable to river flooding are those land forms that owe their existence to the very river that floods them. By far the greatest acreage exposed to flooding in British Columbia are the floodplains of our rivers.

A third category of flooding has been labeled local flooding. This type of flooding may or may not be associated with an extreme event, but rather may be caused by poor or blocked drainage. In some areas flooding occurs annually on agricultural lands without major consequences, other than being a nuisance or degrading the use of the land.

Urbanized or agricultural areas which suffer from poor gravity drainage often need to rely on pumps for drainage assistance. Pump stations are designed to handle a given inflow, which if exceeded can lead to local flooding. Finally, blockage of storm drains, drainage ditches, or natural channels by sediments, debris, or ice may lead to flooding which is localized in nature but may lead to the typically aggravating problems

associated with flooded basements and damaged landscapes.

Work undertaken associated with flood hazards includes predictive and mitigative measures. Predictive measures include basic data collection of snow pack, rainfall, and runoff; statistical analysis of events to quantify the flood threat; modelling of storm events, storm surges, flood routing, water levels, and/or drainage systems and development of floodplain maps.

Flood mitigation includes both active and passive measures. The design, construction and maintenance of storage dams, flood channels, dykes, pump stations, detention ponds, and drainage networks are either preemptive or actively protective flood measures. Raising ground levels and/or elevating structures above predicted flood levels is a widely used and regulated mitigative measure. More passive measures include the control of land use for industrial, agricultural or urban development, where zoning restrictions imposed by regulatory agencies are directed toward flood damage mitigation.

The Federal Agencies involved in work related to flood hazards include Environment Canada and to a lesser extent Agriculture Canada. Environment Canada participates in a cost-share funding with Provinces for flood studies and mitigative measures, and through Water Survey Canada, maintains a network of flow gauging stations throughout Canada.

The Ministry of Environment, Lands and Parks (MELP) is the Provincial Department most actively involved in flood-related work, although Municipal Affairs, Transportation and Highways, and the Solicitor General are involved to a lesser extent. MELP administers joint Federal-Provincial programmes; monitors and maintains snow pack stations; forecasts floods; develops floodplain maps; establishes restrictive covenants on subdivisions within floodplains; and encourages the development of floodplain management guidelines.

Municipalities are largely responsible for developing floodplain management plans; establishing zoning and building bylaws; and, either directly, or through regulatory control, the design and maintenance of storm drainage works.

At least three areas are perceived as being problematic in identifying and managing flood hazards: a lack of public or political awareness as to the risks and damage potential associated with flood threats - particularly in floodplain areas growing with ever increasing industrial and residential populations; a concomitant lack of funds to increase, let alone maintain, the number of data collection stations and preparation of flood protection strategies, without having major flood events provide the incentive for funding; and our ability to identify and rationalize the accuracy of flood level predictions, taking into account the vagaries of nature.

MARINE HAZARDS

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ABSTRACT

Marine hazards due to geological sources will be discussed. In this presentation I do not consider marine hazards due to atmospheric origin. The two important marine hazards of geologic origin are tsunamis due to underwater earthquakes and water waves due to submarine landslides. In the province of British Columbia, the key organizations dealing with these problems fall into three distinct classes. First of all, at least three provincial government ministries are relevant: the Provincial Emergency Program (Ministry of the Solicitor General), B.C. Geological Survey Branch (Ministry of Energy, Mines and Petroleum Resources) and the Water Management Branch (Ministry of Environment, Lands and Parks). In the second category are various departments of the federal government: Pacific Geoscience Center, Geological Survey of Canada (Department of Energy, Mines and Resources), Institute of Ocean Sciences (Department of Fisheries and Oceans) and Emergency Preparedness Canada (Department of National Defense). In the third category one can include the universities and consulting companies.

The main impacts from tsunamis can be understood by considering separately tsunamis from distant earthquakes and tsunamis from local earthquakes. For the British Columbia coast, destructive tsunamis from distant earthquakes can arrive mainly from Alaska, Aleutian Islands and to a lesser extent from the Peru-Chile region. A study by the Sea Consult Marine Research Ltd. of Vancouver under contract with the Institute of Ocean Sciences (I.O.S.) examined the problem of tsunami threat on the B.C. coast from distant tsunamis. In this study, the outer coast alone is considered and the Strait of Georgia-Juan de Fuca Strait and Puget Sound are not included.

Three different computer models were developed to propagate the tsunami from the area of generation to the B.C. coast: a deep ocean model, a shelf model and models for various inlets. The following source regions were used in these simulations: Alaska earthquake of March 1964, Kamchatka earthquake of November 1952, and a major hypothetical earthquake in the Shumagin seismic gap in the eastern part of the Aleutian Island Chain. Maximum tsunami amplitudes and associated horizontal currents are listed at 185 key locations on the B.C. coast.

For tsunamis on the B.C. coast from local earthquakes, two different studies are available. The first one is a joint study between I.O.S. and Science Applications International Corporation, Washington, D.C. The second is a joint study between U.B.C. and I.O.S. These two studies include tsunami effects in the Strait of Georgia and Juan de Fuca Strait.

As for the major problems, we can depend upon the Alaska Tsunami Warning Center (A.T.W.C.) at Palmer, Alaska, and the Pacific Tsunami Warning Center (P.T.W.C.) at Ewa Beach, Hawaii, for warning against tsunamis from distant sources. Even though, in principle, the same techniques should work for tsunamis from local earthquakes also, the short travel times make such a dependence on A.T.W.C. or P.T.W.C. somewhat unsatisfactory.

If the earthquake occurs in the Strait of Georgia-Juan de Fuca Strait-Puget Sound system, then we cannot depend on A.T.W.C. or P.T.W.C. for any timely warning. Indeed we have to develop our own warning system. The same situation holds for any tsunamis generated by submarine land slides, for example, in the foreslope hills in the Strait of Georgia.

THE ROLE OF EMERGENCY PREPAREDNESS CANADA

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INTRODUCTION

Emergency Preparedness Canada has, like most government organizations, changed and evolved over the years. It began as Canada Civil Defence in 1948, and was attached to DND. In 1951 it was transferred to National Health and Welfare. In 1957 a second organization known as Canada Emergency Measures Organization was created in the Privy Council office to provide for continuity of government should there be a nuclear attack on North America."

In 1959 a major re-organization took place. The Civil Defense Organization was abolished and Canada EMO moved to the Prime Minister's office assuming the role of coordinating all civil aspects of defence policy. In 1966 Cabinet tasked EMO with the additional responsibility of coordinating federal response to all peacetime disasters. EMO was moved from department to department over the years.

In 1974 EMO was caught up in general government reorganization and officially became the National Emergency Planning Establishment, better known under the federal identity program name, Emergency Planning Canada. This resulted in a number of changes:

1) the approach to emergency planning and preparedness was changed from preparing for wartime time emergencies to preparing for peacetime emergencies and using these as a basis for wartime civil defence; and,

2) a number of functions that are an integral part of civil preparations for war, such as communications, shelters and radiological defence, were placed within other departments, for example, the shelter program went to Public Works and radiological defence went to DND. A further change occurred in 1984 when the Minister of National Defence was also named minister responsible for emergency planning and our name changed to Emergency Preparedness Canada.

In 1989, after passage of the Emergency Preparedness Act, which formally identified EPC as a separate department (although still reporting to Mr. McKnight as Minister responsible for Emergency Preparedness), EPC was given an expanded mandate. As defined in the Emergency Preparedness Act "The purpose of Emergency Preparedness Canada is to advance civil preparedness in Canada for emergencies of all types, including war and other armed conflict, by facilitating and coordinating, among government institutions and in cooperation with provincial governments, foreign governments and international organizations, the development and implementation of civil emergency plans.

The functions of Emergency Preparedness Canada with respect to the development of civil emergency plans are:

1) to develop policies and programs for achieving an appropriate state of national civil preparedness for emergencies;

2) to encourage and support provincial civil preparedness for emergencies and, through the provinces, local civil preparedness for emergencies;

3) to provide education and training related to civil preparedness for emergencies;

4) to enhance public awareness and understanding of matters related to civil preparedness for emergencies;

5) to analyze and evaluate civil preparedness for emergencies and conduct related research;

6) to provide for the continuity of government during and after an emergency;

7) to establish arrangements with each province whereby any consultation with the Lieutenant Governor in Council of the province required by the Emergencies Act with respect to a

declaration of an emergency under that Act can be effectively carried out; and,

8) to coordinate and support:

   - the development and testing of civil emergency plans by government institutions

   - the activities of government institutions relating to civil preparedness for emergencies with like activities of the provinces and, through the provinces, of local authorities, and

   - in accordance with the external relations policies of Canada, the participation of Canada in activities relating to international civil preparedness for emergencies.

The functions of Emergency Preparedness Canada with respect to the implementation of civil emergency plans are:

1) to monitor any potential, imminent or actual civil emergency and to report, as required, to the Minister and to government institutions on the emergency and any measures necessary for dealing with the emergency;

2) to coordinate or support, as required:

   - the implementation of civil emergency plans by government institutions; and

   - the provision of assistance, other than financial assistance, to a province during or after a provincial emergency; and

   - to provide financial assistance to a province when authorized pursuant to Section 9 (of the Act),

"Emergency Preparedness Canada shall carry out such other functions in relation to civil preparedness for emergencies as the Governor in Council may, by order, specify." What does all this mean on a day to day basis?

HOW CANADA DEALS WITH EMERGENCIES

1) When disaster strikes, the individual is the first line of defence. If the disaster is so severe that individuals can not be expected to cope on their own, they look to their municipal services for help. If the emergency gets beyond local resources, the provincial government may be asked for assistance.

2) Although ready to help at any time, the Government of Canada normally gets involved in an emergency only when a provincial government asks for assistance. The exception is when the emergency or some aspect of it falls within the jurisdiction of the federal government.

3) Usually, EPC knows about a disaster before anyone asks for federal help. Our situation centre in Ottawa monitors emergencies all over Canada. This way, the government is ready to help when needed. Depending on the emergency, the most appropriate department takes the lead on behalf of the Government of Canada, with other departments providing support.

4) Every federal department, crown corporation and agency must plan and prepare to take on emergency responsibilities that relate to their normal functions and resources. For example, Transport Canada plans for assisting in possible disasters involving trains, ships and aircraft; Health and Welfare Canada plans for emergencies involving disease or injury; the Canadian Armed Forces plan and prepare to make their varied capabilities available when needed.

5) EPC planners work with departmental officials to ensure these plans are as effective and as up to date as possible.

FEDERAL/PROVINCIAL COOPERATION

The governments of the provinces, of the territories and of Canada work together in many areas of emergency preparedness. An EPC regional director in each provincial capital is in constant touch with provincial and territorial emergency officials to ensure a country-wide network of preparedness.

POST-DISASTER FINANCIAL AID

In the wake of a major disaster your community or province may face heavy re-building costs. To help provincial governments with the financial burden of their relief measures, EPC administers the disaster financial assistance arrangements on behalf of the federal government. Since 1970 the Government of Canada has paid out more that $100 million in disaster relief to the provinces and territories. Generally, payments are made to help restore personal property, farmsteads, small businesses and public works to their pre-disaster condition.

PLANNING FOR TOMORROW ... TODAY

Planning is the key to handling any disaster. If you know what to do you can keep the damage and human suffering to a minimum. Being prepared is a form of insurance. To foster good planning and promote national preparedness, EPC administers the Joint Emergency Preparedness Program (JEPP) on behalf of the federal government. Roughly $6 million is spent annually to help provinces and territories with emergency preparedness projects. For example, the project may be emergency generators for arctic communities, an emergency response vehicle for the prairies, or a communications network for the eastern provinces, as part of a longer term program to improve a province's overall state of emergency preparedness.

TRAINING AND EDUCATION

EPC gives or sponsors more than 100 courses, conferences and seminars a year at the Canadian Emergency Preparedness College in Arnprior, Ontario. Each year, about 3000 representatives from all levels of government and the private sector are trained in the techniques of emergency planning and management. Most courses run for one week, and topics range from emergency health and welfare services to transportation of dangerous goods. EPC pays travel and living expenses from the time course participants leave home until they return.

RESEARCH

EPC sponsors research related to emergency preparedness. Past projects have included everything from an investigation of computers and their potential application to emergency planning, to an assessment of the economic impact should there be an interruption in Canada's supply of strategic minerals.

SOME KEY PROGRAMS

1) EPC participates in various ways in a number of programs aimed at improving national preparedness for emergencies. Some examples are:

2) CONTINUITY OF GOVERNMENT: The maintenance of a string of emergency operations centres across the country - all of them protected against radioactive fallout and interlinked by communications systems.

3) VITAL POINTS: A program to identify vital facilities, plants and services that would have to be protected if national security were threatened.

4) ESSENTIAL RECORDS: A program to identify and preserve those records that would be essential for government operations during and after a nuclear attack.

5) NATO: Planning activities and exercises related to the civil side of alliance preparedness.

6) CANADA/U.S. COOPERATION: Maintaining close working relationships with our counterpart organization in the United States, the Federal Emergency Management Agency.

Of particular importance to you are:

1) Our responsibility for continuity of government. This program is currently under review and a discussion paper on the REGHQs and who should pay for their upkeep [they are the core of the continuity of government program] is currently being drafted for the Minister. As you are probably aware, although the REGHQs and CEGHQ at CARP are staffed by DND, they belong to EPC; and

2) Our development of a national earthquake response plan for a catastrophic earthquake in

B.C. As you probably have already been told, this plan, if invoked would call upon all of the resources of all federal departments and agencies in B.C. The Director of Regional Operations and the Admiral have already agreed to their full support of B.C. in such an event.

CURRENT PROVINCIAL GOVERNMENT ROLES

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ABSTRACT

The investigation of natural hazards necessitates a multidisciplinary approach involving not only provincial agencies but also local and federal governments. The attached Table and Notes summarize the role of various agencies in geologic hazard identification, management, mitigation, disaster response, and research and information. The table also identifies areas where no organized program of hazard management has been undertaken. The Flood Damage Reduction Program of the Ministry of Environment is perhaps the most comprehensive.

With the authority for hazard management being devolved to the local level of government, which has responsibility for land planning, zoning and regulation of construction, the management of geologic hazards has also been evolving.

Mitigation has not been undertaken as an organized program, except for flood hazards, and then only for the protection of existing development, where it is cost effective and on a cost sharing basis. Mitigation with respect to other hazards has largely been on an ad hoc basis.

Management of development in geological hazard areas is perhaps the most responsible action that can be undertaken and yet hazard management programs have not been initiated for many geologic hazards. The Ministry of Environment, Lands and Parks in conjunction with the Ministry of Municipal Affairs, Recreation and Culture, has initiated a program of liaising with local government to establish management criteria with respect to flooding and erosion under the Municipal Act.

While provincial agencies do identify geologic hazards on an organized or ad hoc approach and address disaster response under the Provincial Emergency Program, there is no unified policy to promote hazard land management in the province.

INTRODUCTION

British Columbia is a unique landscape in which man's development often appears as a hasty and unplanned after thought. The patterns of resource extraction that formed our current development patterns evolved without consideration for the natural hazards that were present in the environment. Often the risks associated with the development from flooding, avalanche, tsunami, landslide and earthquakes were unknown. Into this existing framework of development are thrown the resouce managers of today.

NATURAL HAZARDS

The investigation of natural hazards necessitates a multidisciplinary approach involving all levels of government, academic institutions and individual developers. While the involved agencies have not formed a consolidated approach to natural hazard management, there are significant actions being undertaken that require recognition and consideration if there are to be advances in our abilities to address natural hazards or to regulate development in the vicinity of these hazards.

Table 1 provides a matrix identifying the agencies involved with the identification, management, mitigation, disaster response, and research with the various natural hazards that impact development.

The implication that can be identified from this table is that hazard identification, where it is actively undertaken, is a responsibility of the senior levels of government. Largely it is these senior bodies of government that have the expertise on staff to address the issue and the legislated mandate to be involved with this task. It is worth noting that other than flooding and tsunami, hazard management identification relies on the reactive mechanism rather than a proactive undertaking. The management of development which may be impacted by natural hazards is the responsibility of local governments. While local government may be a reluctant partner in hazard management it has the largest area of responsibility.

Local government is initially involved through the development of Official Community Plans. Persuant to Section 945 of the Municipal Act shall be a written statement including restrictions on the use of land subject to hazardous conditions or that is environmentally sensitive to development. The official community plan also utilizes Development Permit Areas, Section 976 of the Municipal Act, to designate areas for the protection of development from hazardous conditions. The development of Official Community Plans involves many provincial agencies who may be referred to by local government for hazard identification.

Hazard mitigation which involves the forecasting and monitoring of hazards, and the development of engineering works to mitigate the impacts of the hazard has largely been the responsibility of the senior levels of government. This responsibility is associated with the levels of professional staff required to forecast and monitor natural hazards and the significant investment required to develop engineering works, both of which are beyond the capacity of local government. Operation and maintenance of these works is undertaken by local authorities.

Notwithstanding the significant developments that have been made in natural sciences and engineering to identify and manage natural hazards, there is yet to be a unified process at any level of government for hazard management in British Columbia. Table 1 illustrates significant areas where no responsible agency has been identified.

FLOODPLAIN MANAGEMENT

In contrast to the above, flooding is a hazard that has been addressed. Due to the frequency of flooding, the potential for loss of life, property damage and the trauma associated with flooding, a partnership between all levels of government has evolved to address floodplain management, including identification, management, mitigation and disaster response. This program has evolved since the 1948 Fraser River flood which caused significant damage in the Lower Fraser River valley, costing approximately $20 000 000. A similar flood in the Fraser River valley with today's development patterns could translate into billions of dollars of damage were it not for existing floodplain management and protective works.

In response to the 1948 flood, the Federal and Provincial governments initiated the Fraser River Flood Control Program in 1968. While this program was focussed on the development of a dyking system for the Fraser River, it did include a requirement that the province undertake to regulate development in the floodplain. In response to a flood on the North Thompson River in 1972 the Province became involved with floodplain managment. The Land Title Act was amended to include that no lands subject to flooding would be subdivided without the approval of the Minister of Environment.

Hazard identification was initiated in 1974 with the introduction of the Floodplain Mapping program. Under this program significant portions of the larger watercourses of the province have been mapped to assist with hazard management. The program has been augmented with financial assistance from the federal government under the 1987 Floodplain Mapping Agreement.

Flood hazard managment has been significantly increased. Increased development potential in flood prone areas has been regulated under Section 82 of the Land Titles Act. In addition the regulation of new development, in cooperation with local government, has also been increased. Official Community Plans are used to identify flood prone lands and set policy for development in these areas. Floodplain management bylaws have been implemented to ensure that new development in the floodplain is not susceptible to flood damage. Building inspectors are required to be cognizant of the hazard when issuing building permits.

Hazard mitigation has evolved from the initial Fraser River Flood Control program. Flood forecasting is undertaken on the Fraser River and several other systems where major urban development is located in the floodplain. Mitigative works are undertaken on a variety of scales to ensure that existing development (that development which proceeded the hazard management aspect of the program) is protected from flooding and erosion. Dyke inspection is coordinated with local government to ensure that any mitigative works are maintained in correct operating order.

Disaster response, including preparedness, response and recovery, is coordinated between the local government, the Provincial Emergency program and the Ministry of Environment, Lands and Parks.

CONCLUSION

While the floodplain management program of the Ministry of Environment, Lands and Parks has been displayed as an example of a hazard management program, it is a program that is still evolving. However, what this review does suggest, is that hazard management is not the responsibility of any one agency or level of government. Cooperation between the various levels of government is required to ensure that development is undertaken in recognition of the hazard.

However, that cooperation must yet be formed for various other natural hazards other than flooding. While local government has been provided the tools and responsibility for hazard management under the Municipal Act, it does not have the resources available to undertake hazard identification, mitigation or research. These areas are the responsibility of the senior levels of government. If, as a society, we wish to ensure that new development is protected from natural hazards, then consideration may be given to ensuring that all resource agencies actively coordinate with each other to assist local government with hazard management.

Table 1. Province of British Columbia-Roles in Geological Hazards and Relevant British Columbia Government Legislation/Programs Respecting Natural Hazards.

	FLOODING	TSUNAMI	LANDSLIDE	AVALANCHE	EARTHQUAKE
IDENTIFICATION	*ENV(1)	*IOS	-	-	*Building Code
MANAGEMENT					
-Subdivisions	ENV(2)	ENV(2)	HWY/Local(3)	HWY/Local(3)	-
-Community Plans	Local(5,6)	Local(5,6)	(5)	(5)	Building Code
-Building Inspection					
Building Code	-	-	-	-	Local
Geotech Report	Local(7)	Local(7)	Local(7)	Local(7)	
-Crown Lands	Hazards identified by Referral to Provincial Agencies and Local Authorities(8)				
MITIGATION					
-Forecast/Monitor	*ENV	*IOS/PEP	-	-	*PGC
-Works	*ENV(11) Local	-	-	-	-
-Operation/Maint.	ENV(10)	-	-	-	-
DISASTER RESPONSE					
-Preparadness	Local PEP ENV	Local PEP	Local PEP	Local PEP	Local PEP
-Response	Local *PEP(12) ENV/HWY	Local *PEP(12)	Local *PEP(12)	Local *PEP(12)	Local *PEP(12)
	Response Involvement by all Provincial Agencies as Required				
-Recovery	Local *PEP(12) ENV/HWY	Local *PEP(12)	Local *PEP(12)	Local *PEP(12)	Local *PEP(12)
	Recovery Involvement by all Provincial Agencies as Required				
RESEARCH/ INFORMATION	ENV	IOS	MOF EMPR HWY ENV	HWY	PGC
	*Research/Information-Universities, NRC, GSC, and Federal Agencies				
OPERATIONAL	Individual Provincial Agencies Within Area of Operation				

NOTES:

	AGENCY	HAZARD	ASPECT
1) Agreement Respecting Floodplain Mapping in BC	*ENV	Flooding	Identification
2) Sect. 82/85 Land Titles Act	ENV	Flooding Erosion	Management Management
3) Sect. 86 Land Titles Act	HWY Local	All All	Management Management
4) Municipality Enabling and Validating Act	MARC	Flooding	Management
5) Municipal Act Sect. 945, Community Plans	MARC	All	Management
Municipal Act Sect. 952, Rural Land Use		All	Management
Municipal Act Sect. 970, Non Conforming		All	Management
Municipal Act Sect. 976, Development Permit		All	Management
Municipal Act Sect. 978, Tree Cutting		All	Management
6) Municipal Act Sect. 969, Floodplain Elevation	MARC ENV	Flooding	Management
7) Municipal Act Sect. 734, Geotechnical Report	Bldg. Inspector	All	Management
8) Land Act Sect. 8 (Inter-Agency Referral)	MCL	All	Management
10) Dyke Maintenance Act	ENV	Flooding	Mitigation
11) Flood Protection Program	ENV	Flooding	Mitigation
River Protection Assistance Program	ENV	Flooding	Mitigation
Fraser River Flood Control Program	*ENV	Floodin	Mitigation
12) Disaster Financial Assistance Program	*PEP	Flood/Landslide	Response/Recovery
Environment Management Act	ENV	All	Response

MCL	Ministry of Crown Lands
ENV	B.C. Ministry of Environment, Lands and Parks
HWY	B.C. Ministry of Transportation and Highways
MARC	Ministry of Municipal Affairs, Recreation and Culture
PEP	Provincial Emergency Program
EMPR	Ministry of Energy, Mines and Petroleum Resources
MOF	B.C. Ministry of Forests
IOS	Institute of Ocean Sciences
PGC	Pacific Geoscience Centre
Local	Local Authorities, Regional District, Municipality, City, Town, etc.
*	Federal Government Participation
-	No Designated Authority

SHORELINE EROSION IN BRITISH COLUMBIA

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ABSTRACT

As a natural occurrence shoreline erosion is an outcome of the geomorphic development of coastlines and lakesides. The erosion can be a cyclic catastrophic event or a slow but steady and ongoing process. Activities by man can also trigger erosion through interruption or alteration of the natural physical processes. The erosion becomes a hazard when there is a threat of economic loss, loss of life or loss of habitat. Catastrophic events are generally rare in B.C., being linked to extreme events of high tides combined with large storms.

The foreshore erosion process is governed directly by such factors as sediment supply, sediment character, oceanographic conditions of tides, waves and currents, and the geomorphic structure of the coastline. Additional factors affecting erosion are groundwater conditions, vegetative cover land use, subsidence and freeze-thaw cycles. The shoreline of any specific site will be eroding, accreting, in static equilibrium where the sediments are trapped between rigid geomorphic features, or in a state of dynamic equilibrium requiring a continued supply of littoral sediment.

There are four areas into which shoreline erosion along the B.C. coast might be classified: beach or foreshore erosion; upland or backshore erosion; local erosion around structures; and sub-tidal slope failures. Sub-tidal erosion in B.C. commonly occurs through catastrophic failures of delta fronts at the heads and side of fjords. A good example is the 1971 subsidence at Kitimat which resulted in property damage from the failure, and from the large water surface fluctuations which followed.

Upland erosion is often preceded by erosion of the foreshore, the most obvious example being the recession of the high bluffs typical of the Quadra Sand formation at locations such as Point Grey and Willemar Bluffs at Comox. These sandy bluffs naturally recede through slope failures, gullying and washouts with subsequent loss of talus material by wave and tidal action. Erosion of the bluffs can be forced through disturbance or removal of any adjacent foreshore armoring material leading to a lowering of the beach which bounds the bluff face.

Glacial submergence followed by isostatic rebound and changing sea levels have all played a part in the development of these armored foreshores which are characteristic of much of the B.C. coastline. The armoring consists of a single layer of cobble to boulder sized material that has formed as a blanket on the foreshore surface through loss of the smaller fraction of the sediment matrix. This delicate balance can be upset through disturbance of the armour layer and exposure of the underlying matrix which often results in rapid erosion while a new armour layer forms. The extent of the erosion is then related to the fraction of armour sized material within the sediment matrix.

Other mechanisms for erosion derive from the local effect that structures such as seawalls, groynes, pilings etc. have on intercepting sediment transport or altering the wave geometry through diffraction, refraction and reflection. The channel dredged to provide fill for the Tsawwassen causeway provides an example where wave energy is funnelled along the channel through refraction and focussed onto the adjacent shoreline resulting in local erosion.

Incidents of shoreline erosion are typically dealt with in a reactive manner through direct application of protective measures. Not in all cases are the coastal processes fully understood or studied and the erosion problem is often transferred to a new location down coast. Direct protective measures, although the most apparent solution, are not the only method for shoreline stabilization. Indirect protection through manipulation of the local oceanographic and geomorphic processes can be very effective while at the same time maintaining or enhancing the natural character of

the shoreline especially to the benefit of marine habitat.

Current public activities have focused on resource mapping of the shoreline and regulatory activities concerned with use, navigation, and fish habitat, leaving erosion issues typically to be addressed by upland owners as needs arise. There is a need for management of the coastal zone and its physical processes through control of activities and preservation and enhancement of its unique features. Public and political awareness of the coastal zone and the impacts of shoreline erosion will have to be raised to a higher level to precipitate the commitment and the necessary funding.

EARTHQUAKE HAZARD IN BRITISH COLUMBIA

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ABSTRACT

In British Columbia earthquake hazard is highest in the coastal regions, where seismicity associated with a subduction regime dominates in the populated region of southwest B.C., and the seismicity associated with a large strike-slip fault zone dominates in the Queen Charlotte Islands region. The hazard distribution is documented in the seismic hazard maps published in the supplement to the National Building Code of Canada. Major earthquakes have occurred in these regions in the past and small earthquakes are frequent. Minor earthquakes occur all across the province with the few damaging level earthquakes that have occurred away from the coast in historic time being located along the eastern margin of the Cordillera.

Almost all data collection and most analysis and research pertaining to earthquake hazard assessment in British Columbia is carried out or funded through the Geological Survey of Canada's facility at the Pacific Geoscience Centre (PGC) in Sidney, British Columbia. The following activities are carried out at PGC:

Seismicity monitoring
Strong motion recording
Earthquake intensity surveys
Earthquake information service
Seismic hazard research
Earthquake source properties research
Crustal deformation research

The annual operating budget of Earthquake Studies at PGC is about $350 000. This includes a recent (beginning 1989) increase of $140 000 to enhance the study of seismic hazard on the west coast. In addition about $150 000 in special purpose funds for seismic hazard assessment to hydrocarbon development in the western Arctic and Queen Charlotte Islands regions is administered by PGC. Most of the operating budget goes to private contractors to operate the 50 station seismic network and 40 instrument strong motion network in western Canada and to carry out crustal deformation surveys. The capital acquisitions budget varies considerably from year to year and is currently at an all time high as we are in the first year of a three year upgrading of the Canadian National Seismograph Network; the first since it was installed in the early 1960's.

The staff in Earthquake Studies at PGC consists of twelve people, four of whom are research scientists. Three of the twelve people have been transferred into the group in the last year.

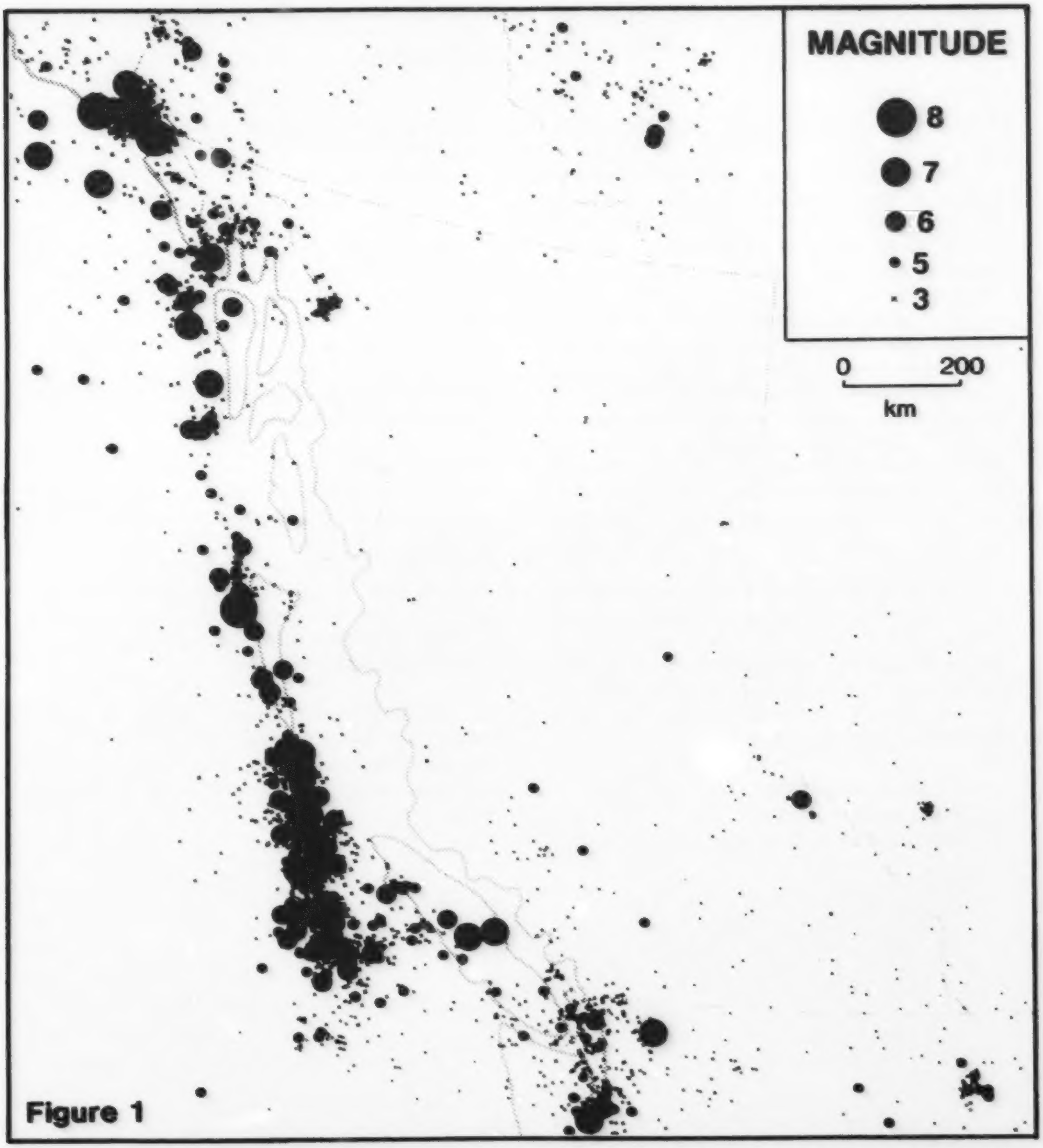

Figure 1

Figure 1: Earthquakes of magnitude 3 and greater up to the end of 1986 from the Canadian Earthquake Epicentre File. Magnitude 3 is about the size of earthquake that is felt generally throughout a region. Many hundreds of earthquakes that are too small to be felt or are slightly felt are also located each year and are included in this data file. Earthquakes shown by dots are those capable of causing damage and dot size is scaled with earthquake magnitude. British Columbia has experienced a number of damaging level earthquakes within and immediately adjacent to its borders in historic times.

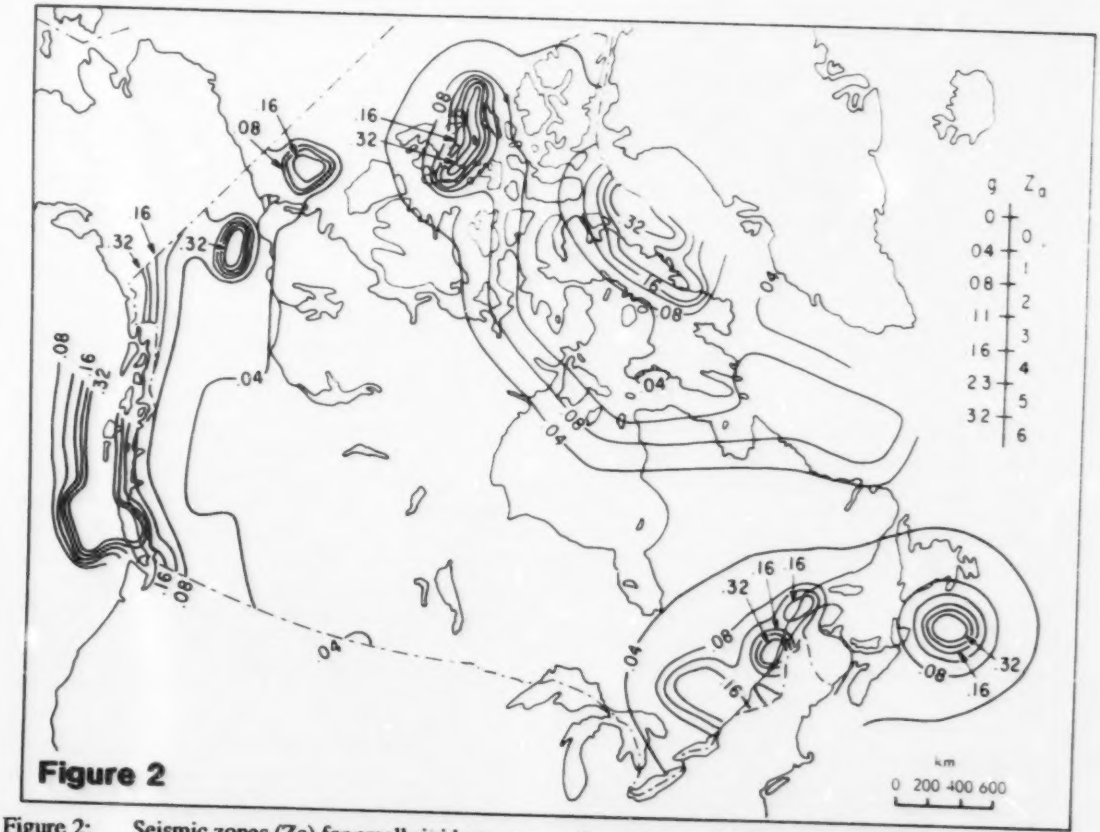
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Figure 2

Figure 2: Seismic zones (Za) for small rigid structures. Contours are of peak hroizontal ground accelerations on firm ground expressed in units of g (i.e. force of gravity = 1), having a probability of exceedence of 10 per cent in 50 years. From the Supplement to the 1985 edition of the National Code of Canada, Chapter 4, Commentary-J.

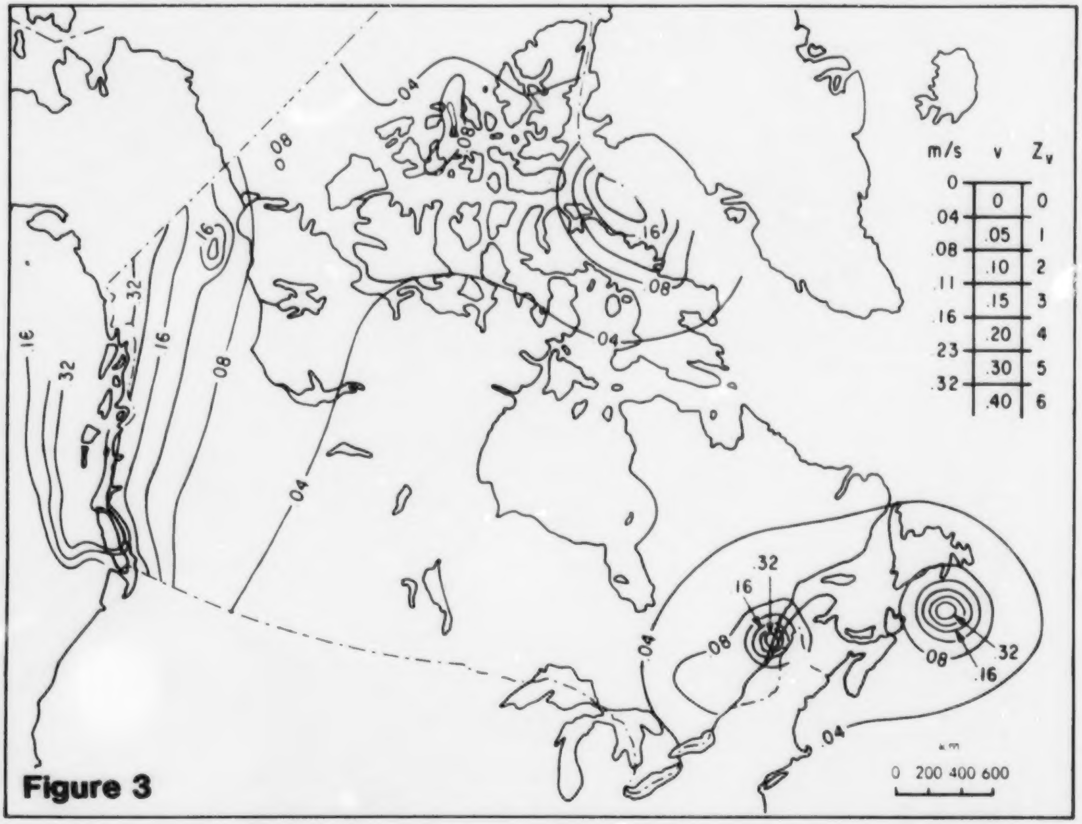
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Figure 3

Figure 3: Seismic zones (Zv) for large structures. Contours are of peak horizontal velocity on firm ground expressed in m/s, having a probability of exceedence of 10 per cent in 50 years. From the Supplement to the 1985 edition of the National Building Code of Canada, Chapter 4, Commentary-J.

LOCAL GOVERNMENT LEGISLATIVE FRAMEWORK

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ABSTRACT

Hazard land management involves a variety of roles and responsibilities including:

- *identification*
- *information*
- *planning*
- *regulation*
- *administration*
- *enforcement*
- *mitigation*
- *disaster response*

While the Province has primary responsibility, local governments in British Columbia have an important but complex role to play in the system of managing development in areas of natural hazards. This role derives partly from statutory requirements delegated by the Province, local government as well as from the statutory authority which enables other local initiatives and actions.

Notwithstanding the statutory requirements, perhaps the most important element is the attitude or approach of the local government toward assuming the responsibility for the management of development in hazard areas. Local government Councils and Boards can exercise discretion about the extent to which they wish to become involved.

A variety of Provincial legislation relates to the activities of local governments but the Municipal Act is the most significant piece of legislation as it provides the statutory authority and framework for local governments to operate, including the role for managing development in hazard areas.

Provincial legislation basically does two things: it directly establishes requirements or procedures, or, it enables local governments to enact or establish their own procedures or requirements. The last 10 years have seen major changes to the legislative framework for hazard management. There has been an increase in the variety and complexity of planning, regulatory or enforcement opportunities. There has also been an increasing delegation of authority for hazard management to the local government level. Major changes to the Municipal Act in 1985 resulted in new regulatory opportunities and requirements for hazard management. For example, Section 969 provides the authority for the establishment of floodplain elevations or setbacks and Section 734 (2) enables a building inspector to require a geotechnical report for areas he considers to be hazardous.

While legislative opportunities exist for an active positive role for local government, many are reluctant to get involved due to major concerns for liability. Appropriate studies are also expensive to undertake and often it is difficult to assess questions of risk and probability in relation to the technical evaluation.

In the future, legal interpretations and court cases will help define and clarify the present system of hazard management. The existing system can also be improved through greater coordination between agencies and levels of government. New legislative initiatives may also be introduced to streamline procedures, to more clearly define the roles of various authorities, to further delegate responsibility, and to enhance and clarify the role of local government. Such initiatives should take place within a broader strategy for the management of development in areas of natural hazard.

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